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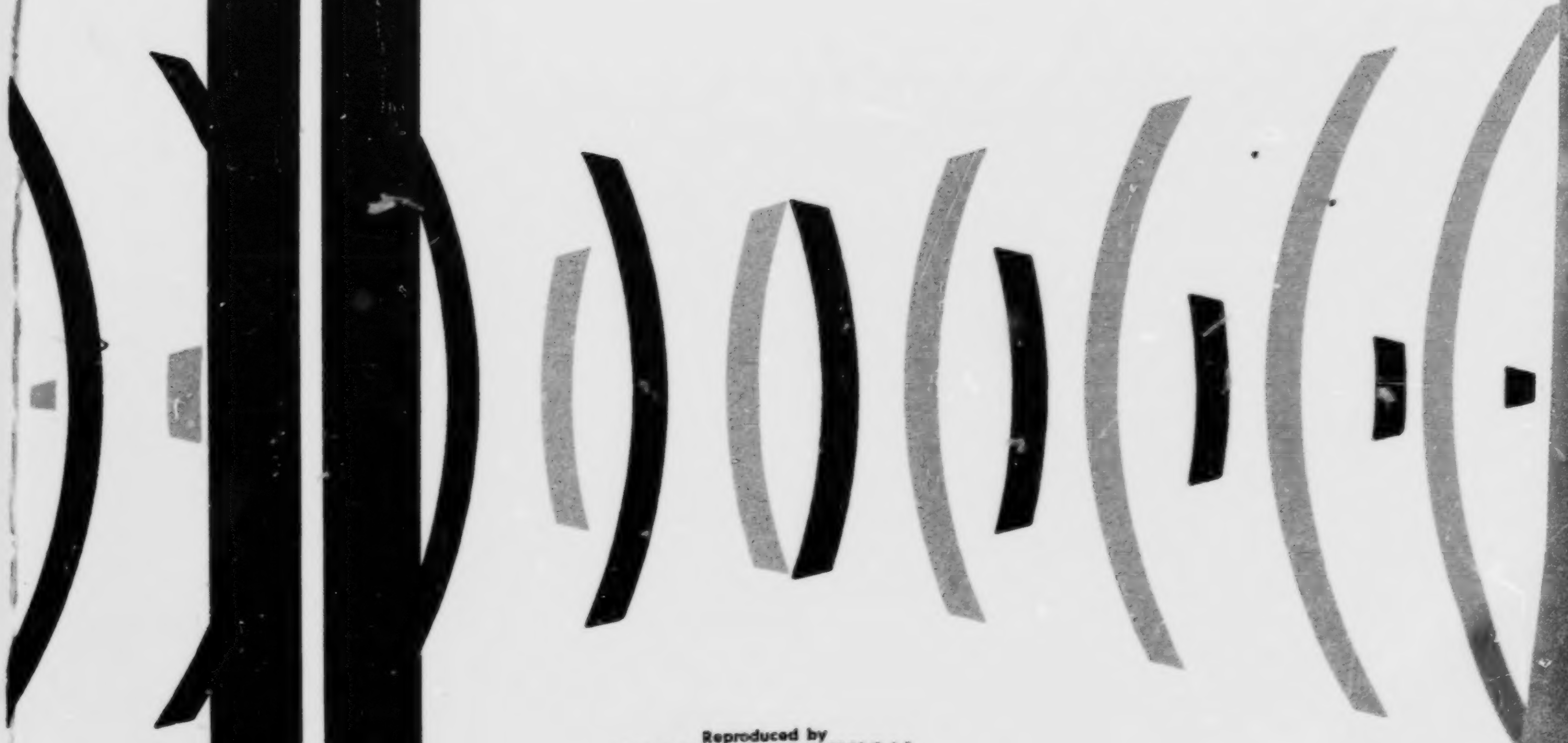
RADIATION SAFETY in X-RAY DIFFRACTION and SPECTROSCOPY



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RADIATION SAFETY in X-RAY DIFFRACTION and SPECTROSCOPY

Proceedings of a Conference held on

January 6-7, 1970
at the University of Pennsylvania
Philadelphia, Pennsylvania

Edited by

Thomas M. Moore and Walter E. Gundaker
Division of Electronic Products

and

John W. Thomas
University of Pennsylvania

Sponsored by

American Crystallographic Association

Delaware Valley Chapter
Health Physics Society

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U.S. Public Health Service
Bureau of Radiological Health

September 1971

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
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The papers included in this Proceedings were submitted by the individual authors as written versions of the papers presented at the Conference on Radiation Safety in X-ray Diffraction and Spectroscopy. The discussions have been compiled from transcripts made during the conference. Editorial changes in the papers and transcriptions have been limited to minor modifications for consistency of style. The opinions stated are those of the authors (participants) and may not represent the policy of the Bureau of Radiological Health or any of the other sponsoring organizations.

FOREWORD

The Bureau of Radiological Health continues to carry out a national program designed to reduce the exposure of man to hazardous ionizing and nonionizing radiation.

Within the Bureau, the Division of Electronic Products (1) develops and administers performance standards for radiation emissions from electronic products, (2) studies and evaluates emissions of and conditions of exposure to electronic product radiation and intense magnetic fields, (3) conducts or supports research, training, development, and inspections to control and minimize such hazards, and (4) tests and evaluates the effectiveness of procedures and techniques for minimizing such exposures.

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I encourage the readers of these reports to inform the Bureau of any omissions or errors. Your additional comments or requests for further information are also solicited.

John C. Villforth

John C. Villforth
Director
Bureau of Radiological Health

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PREFACE

This publication contains the proceedings of the Conference on Radiation Safety in X-ray Diffraction and Spectroscopy, which was held on the campus of the University of Pennsylvania, Philadelphia, Pennsylvania, January 6-7, 1970. The need for such a conference became apparent when it was realized that there was inadequate communication between the health physicists concerned with the safety of x-ray diffraction and spectroscopy equipment, the user of this equipment, and the governmental agencies that have regulatory responsibilities for its safety.

The purpose of this conference was to discuss radiation safety in the use of x-ray diffraction and fluorescence equipment from the viewpoint of the experimentalist and other user-oriented persons as well as that of individuals concerned primarily with radiation safety. Experienced representatives of these groups were brought together to stimulate an exchange of ideas and discussion of programs and practical solutions of major concern. Free discussion was encouraged and practical considerations emphasized. There were no specific recommendations made by the participants as a group, but it is hoped that these proceedings will be a valuable source of information to all interested parties -- users of equipment, health physicists, equipment manufacturers, and others who may be concerned with preparing and implementing radiation safety guides, standards, or regulations.

Robert L. Elder

Robert L. Elder, Director
Division of Electronic Products
Bureau of Radiological Health

ACKNOWLEDGEMENTS

The time and effort of many individuals is required for a conference of this scope to be successful. The assistance of each and every member of the Conference Planning Committee is gratefully acknowledged.

In particular, credit should be given to Mr. Joel Lubenau and to Dr. Reuben Rudman for their efforts in securing a number of the excellent speakers at the Conference. Mr. Lubenau also contributed greatly to the initial organization of the Planning Committee, to the securing of sponsors, and to the editorial review of the Proceedings. Credit should also be given to Mr. Albert A. Maier of Frankford Arsenal whose search for information for use in his safety program led directly to the planning and holding of the Conference.

The staff of the University of Pennsylvania Radiation Safety Office arranged the details of registration, refreshments, audiovisual aids, and information services. The Laboratory for Research in the Structure of Matter (LSRM) of the University of Pennsylvania contributed the excellent meeting facilities, and the helpful cooperation of a number of LSRM staff members is appreciated. Particular thanks are expressed to Mr. Henry Katz, the X-ray Laboratory supervisor, who made possible the successful tour of the LSRM laboratory facilities.

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CONTENTS

Page

FOREWORD iii

PREFACE v

ACKNOWLEDGEMENTS vi

ABSTRACT ix

WELCOME AND OPENING REMARKS 1

S. Reid Warren, Jr., Sc.D. 3
Rodney Ice, Ph.D. 4

SESSION A - INTRODUCTION 5
Moderator: *Richard H. Chamberlain, M.D.*

USES AND USERS OF ANALYTICAL X-RAY EQUIPMENT
William Kehl, Ph.D. 7

DISCUSSION 29

MEDICAL CONSIDERATIONS
Frederick Urbach, M.D., and P. Donald Forbes, Ph.D. . . . 31

DISCUSSION 56

PUBLIC HEALTH EXPERIENCE IN X-RAY DIFFRACTION
Hanson Blatz 60

DISCUSSION 65

SESSION B - ANALYTICAL X-RAY EQUIPMENT AND ITS USE 69
Moderator: *Reuben Rudman, Ph.D.*

SURVEY OF X-RAY DIFFRACTION AND X-RAY SPECTROSCOPY EQUIPMENT
Reuben Rudman, Ph.D. 71

DISCUSSION 75

SAFETY DEVICES FOR X-RAY DIFFRACTION
Sten Samson, Ph.D. 76

DISCUSSION 97

RADIATION SAFETY AND X-RAY DIFFRACTION TECHNIQUES
R. A. Young, Ph.D. 98

DISCUSSION 129

Page

SESSION C - RADIATION SAFETY 131
Moderator: *John C. Villforth*

RADIATION SAFETY: OBJECTIVES AND CONSIDERATIONS
John W. Thomas 133

THE RESPONSE OF VARIOUS SURVEY INSTRUMENTS TO LOW-ENERGY X RAYS
Ray A. Els 141

DISCUSSION 160

ROUTINE RADIATION MONITORING
Rodger W. Granlund 167

ADVANCED DOSIMETRY AND EXPOSURE EVALUATION
Joel O. Lubenau 178

DISCUSSION 193

SESSION D - GUIDES, STANDARDS, AND REGULATIONS 195
Moderator: *Robert O. Gorson*

UNDERSTANDING GUIDES, STANDARDS, AND REGULATIONS
Robert O. Gorson 197

REGULATOR'S VIEWPOINT
John C. Villforth 200

MANUFACTURER'S VIEWPOINT
W. D. Ashby 206

THE USER'S VIEWPOINT ON X-RAY DIFFRACTION SAFETY STANDARDS
Stanley Block, Ph.D. 211

QUESTION AND ANSWER SESSION 215

CLOSING REMARKS 223

John W. Thomas 225
Rodney Ice, Ph.D. 227

APPENDIX A - LIST OF REGISTRANTS 229

ABSTRACT

A conference on radiation safety in x-ray diffraction and spectroscopy was held at the University of Pennsylvania on January 6-7, 1970, to fill the need for improved communications between users of x-ray diffraction and spectroscopy equipment, health physicists, and governmental agencies with regulatory responsibilities. Radiation safety in the use of the equipment was discussed from the viewpoints of the experimentalist and other user-oriented personnel, individuals concerned primarily with radiation safety, and agencies responsible for developing and enforcing guides, standards, and regulations. This report contains the conference proceedings; it includes both the papers presented and the discussions held at the conference.

RADIATION SAFETY IN
X-RAY DIFFRACTION AND SPECTROSCOPY

WELCOME
S. Reid Warren, Jr.,Sc.D.

OPENING REMARKS
Rodney Ice, Ph.D.

WELCOME

S. Reid Warren, Jr., Sc.D.
University of Pennsylvania

In considering what might be said very briefly as a welcome, something has occurred to me which is based on a long experience with various fields of applied radiation. I have watched physicists, chemists, physicians, technicians, biochemists, biophysicists, and others working with radiation. The tendency, of course, is for the person doing research or engineering investigation or clinical work, to pay specific attention to the area in which he is an expert. This is not only natural, but it must be encouraged.

Radiation is not only a useful agency; it is also a dangerous one. So it is that every one of the specialists, every one of you, must pay some attention to safety as well. Here, hopefully, there are those who specialize in safety, who can join together and work with the specialist who is using radiation for research or other purposes. This combination seems to be developing very effectively.

Accordingly, I was delighted when I learned from John Thomas about a year ago that this meeting was being considered as a possible place for discussion among the persons interested in various applications of radiation and those who were concerned with protection.

Although I think that we have far too many meetings in this country, there are times when I think that a meeting can be of extreme value, and this seems to me to be one of them. I think the program is well conceived, and I should like very much to be able to be with you throughout a large part of your deliberations.

I have taken enough of your time. May I welcome you to the University of Pennsylvania. If you find things here that you want to investigate further by visiting or talking to people, or if you find things that you need to complain about, don't hesitate to do so.

OPENING REMARKS

Rodney Ice, Ph.D.
Temple University

I would like to second Dr. Warren's welcome to you and welcome you to the Delaware Valley for this symposium regarding x-ray diffraction usage and equipment.

This is our second symposium. The first symposium was held one year ago on Thermoluminescence Dosimetry and was sponsored by our local chapter of the Health Physics Society. That symposium led, of course, to this second conference.

I want to say a word of thanks to John Thomas and his Committee for all of the background work that has gone into the preparation of this meeting.

There have been four associated sponsors of this meeting, to which I think we should give due credit. The American Crystallographic Association, the Delaware Valley Chapter of the Health Physics Society, the Delaware Valley Section of the Society of Applied Spectroscopy, and, of course, the United States Public Health Service.

SESSION A

INTRODUCTION

Moderator: Richard H. Chamberlain, M.D.
University of Pennsylvania

USES AND USERS OF ANALYTICAL X-RAY EQUIPMENT
William Kehl, Ph.D.

MEDICAL CONSIDERATIONS
Frederick Urbach, M.D., and P. Donald Forbes, Ph.D.

PUBLIC HEALTH EXPERIENCE
Hanson Blatz

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USES AND USERS OF ANALYTICAL X-RAY EQUIPMENT

William L. Kehl,Ph.D.
Gulf Research and Development Company
Process Research Division
Pittsburgh, Pa. 15230

Introduction

The purpose of my talk at this Conference is to present a summary description of the nature of the uses and users of x-ray diffraction and spectroscopic equipment in order to provide a convenient background for the discussions of the various specific topics that follow on the program. I will describe briefly the production and nature of x rays together with some typical applications of these x-ray methods, indicating the type of problems that can be solved, the type of personnel that are likely to be involved with the apparatus, the relative difficulty of performing the experimental work, the nature of the hazards involved, and the precautions that should be observed.

The Production and Nature of X rays

A schematic diagram of a typical x-ray tube and electric circuit is shown in figure 1. The filament is heated with a small electric current and a high voltage is applied between this hot filament and the target. Electrons are accelerated from the filament to the target, and x rays are produced when these high-energy electrons are stopped in the target. Much of the energy of this electron beam is converted into heat, and water cooling is provided to prevent the target from melting.

The nature of the x rays produced is a function of the accelerating voltage applied between the filament and the target, and the composition of the target. The beam from an x-ray tube consists of a continuous spectrum with characteristic spectral lines superimposed on this continuous spectrum, as shown in figure 2. As the accelerating voltage applied to the x-ray tube increases, the envelope of the continuous spectrum is shifted to shorter wavelengths (higher energy) and the integrated intensity increases exponentially, as shown in the diagram in figure 2a. Figure 2b shows the spectral distribution curves for a copper target and a molybdenum target tube, each operated at approximately 35 kV. The characteristic K series appear as sharp, very strong lines, the wavelengths of which are characteristic of the target element. The origin of these characteristic lines is shown schematically in figure 3.

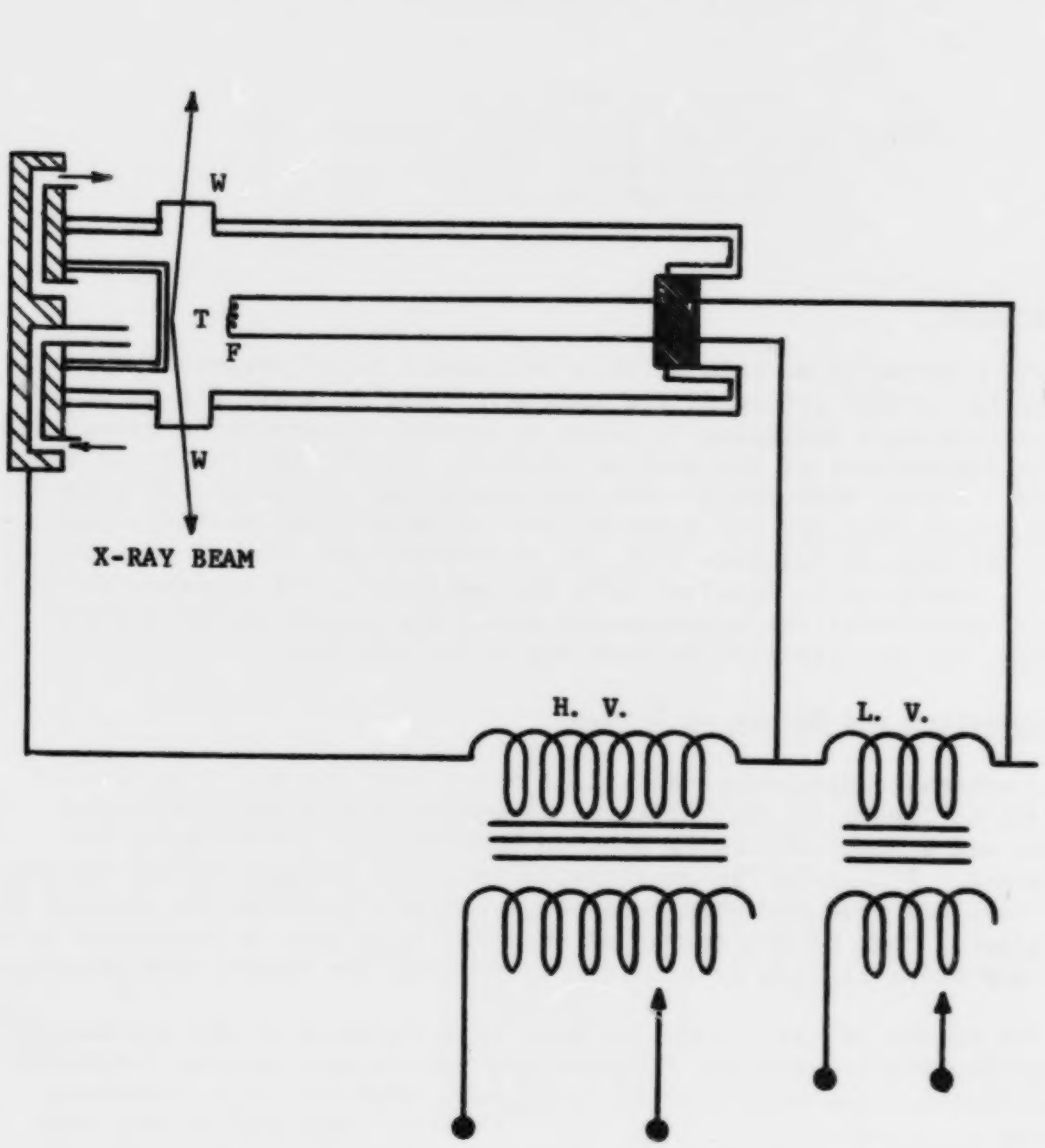
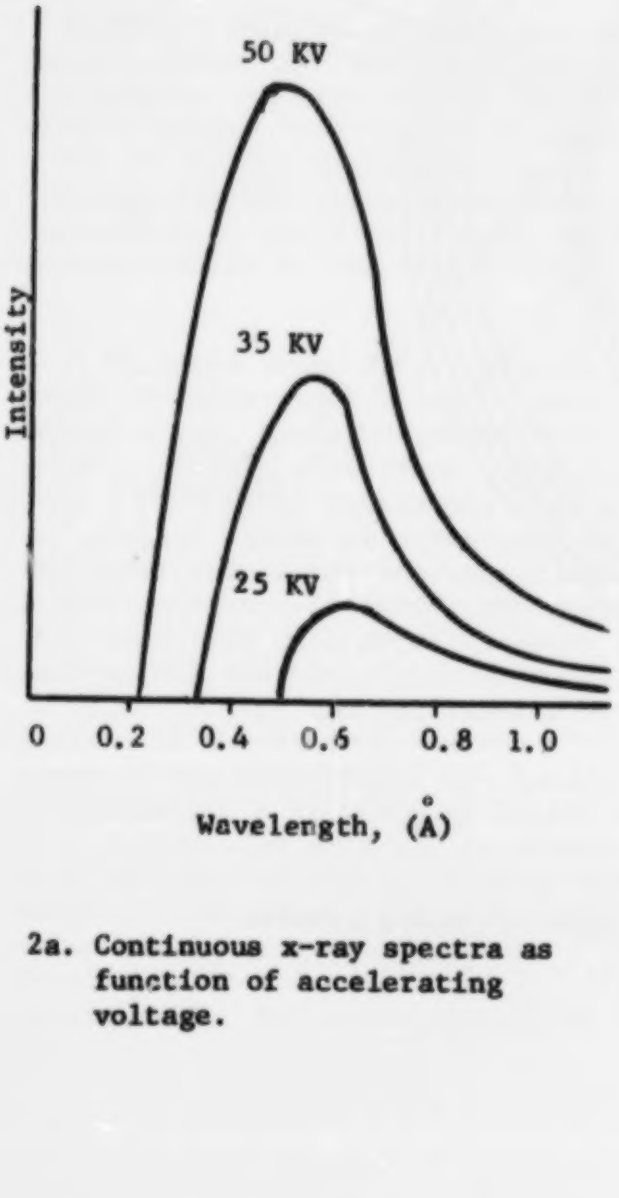
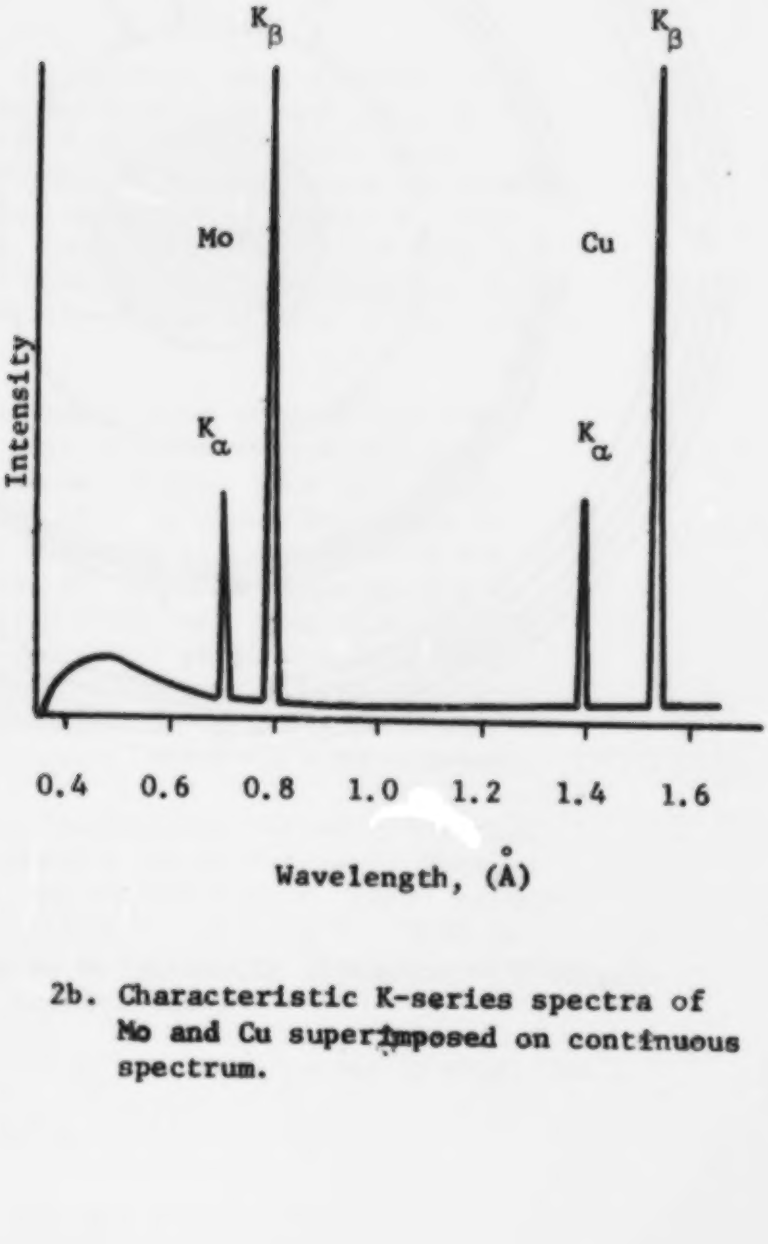


Figure 1. Schematic view of x-ray tube and electric circuit. T, water-cooled target; F, tungsten filament; W, windows; H.V., high-voltage transformer; L.V., low-voltage transformer.



2a. Continuous x-ray spectra as function of accelerating voltage.



2b. Characteristic K-series spectra of Mo and Cu superimposed on continuous spectrum.

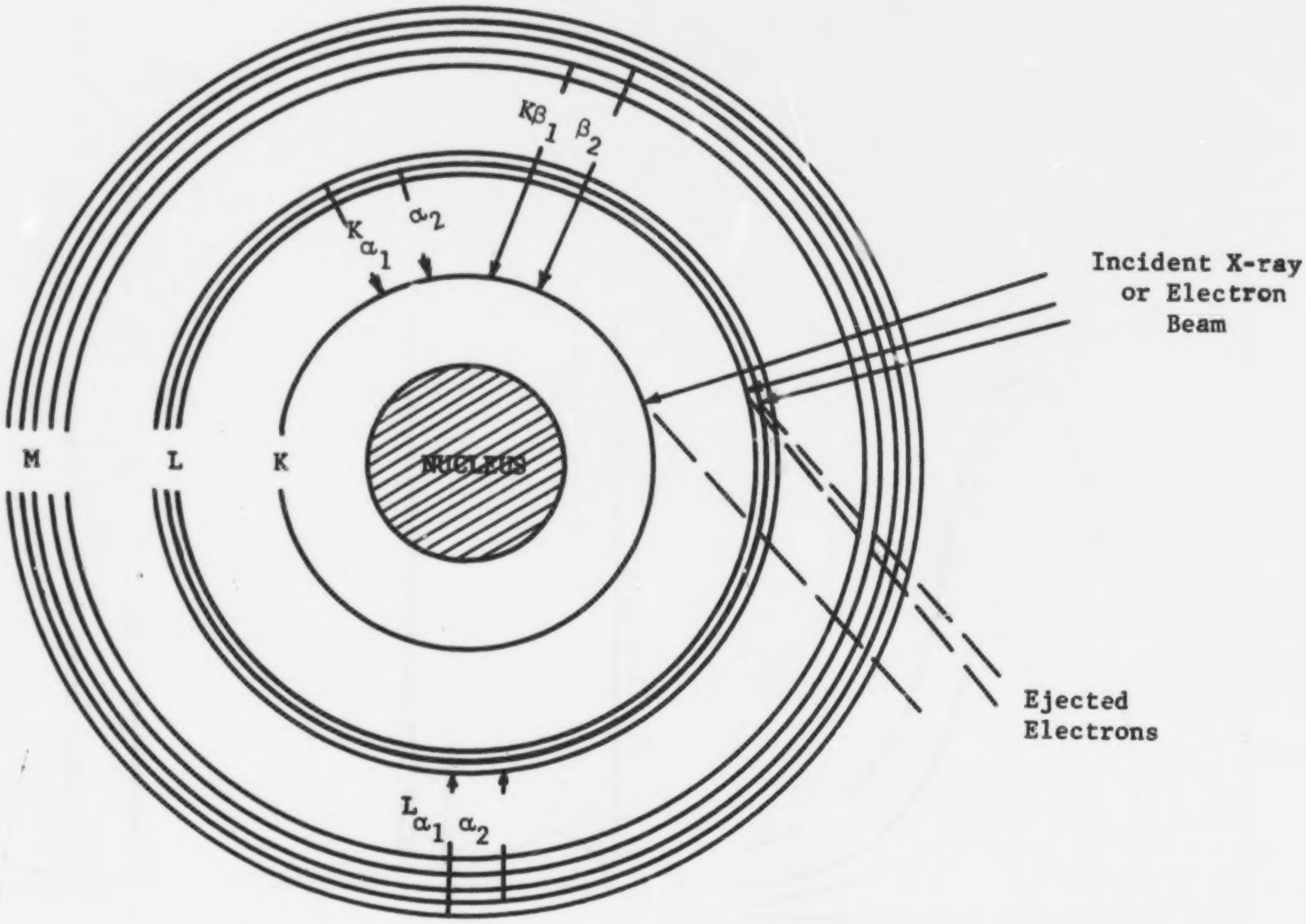


Figure 3. Schematic illustration of the origin of characteristic x-ray spectra.

When electrons or x rays of sufficient energy are absorbed by an atom, electrons will be ejected from the K, L, and M energy levels. When electrons from outer levels fall into the vacancies so created, x rays are emitted, and these constitute the characteristic x-ray spectrum. The K-series lines arise when a vacancy in the K-level is filled, the L-series lines arise when a vacancy in the L-level is filled, etc. The wavelengths of these lines are very specific and characteristic of the atom from which they originate, and this forms the basis of elemental analysis by fluorescent x-ray spectroscopy. On the other hand, these sharp characteristic lines also constitute the source of high-intensity monochromatic (single wavelength) x rays that are utilized in x-ray diffraction.

X-ray Diffraction

When a beam of monochromatic x rays is incident upon a sample of matter, the x rays are scattered in all directions from each atom in the sample. In crystalline materials, the atoms are arranged in an orderly manner, and can be visualized as lying on sets of parallel planes drawn in various directions in the lattice, as shown in figure 4. The spacings between these planes depend upon their orientation and upon the separation of the atoms in the lattice. These interplanar spacings are characteristic of the lattice type and the crystal structure of the sample.

When the atoms in a substance are arranged in an orderly lattice array, interferences arise between the x rays scattered from the different atoms, with the result that x-ray beams emanate from the sample in only certain directions. The reason for this is shown in figure 5. When a wave front containing rays such as M & O is incident upon a set of parallel planes of atoms such as EE' and FF' in a crystalline solid, the interference between the waves scattered from each atom will be destructive except in directions where the scattered waves are in phase. This condition will occur whenever the path difference between two waves, such as MAN and OBP, is equal to an integral number of x-ray wavelengths. In figure 5 this path difference is CB plus BD. Since $CB = BD = d\sin\Theta$, where d is the spacing between planes of atoms and Θ is the angle of incidence of the wave front, the condition for "reflection" of an x-ray beam of wavelength λ is given by $2d\sin\Theta = n\lambda$, where n is an integer. Thus, in a crystalline material, a diffracted x-ray reflection or "line" arises from each set of planes of atoms having a different spacing d. This is further illustrated in figure 6 which indicates how x-ray "powder" patterns arise and are recorded on film. These patterns also may be recorded electronically by means of an x-ray diffractometer which is shown schematically in figure 7. The x-ray tube is at T, and the x-ray beam passes through the

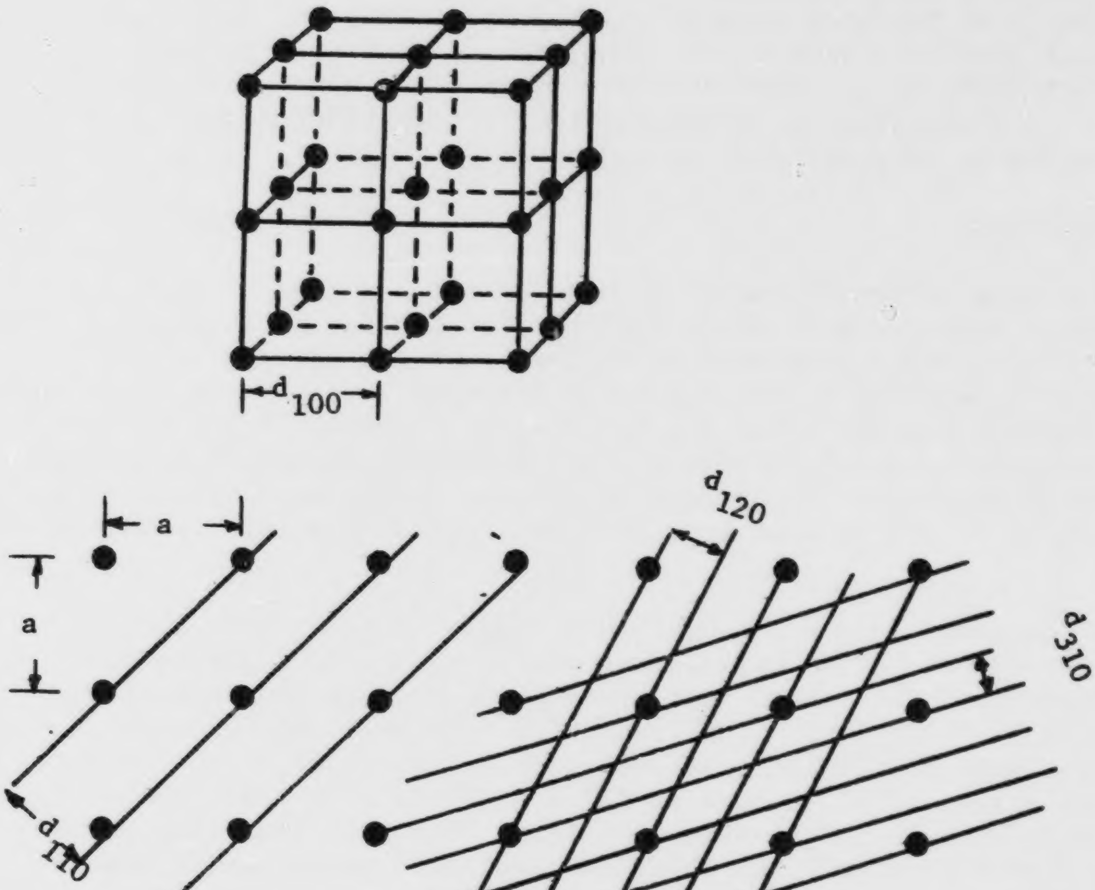


Figure 4. Spacings of some planes of atoms in a cubic lattice.

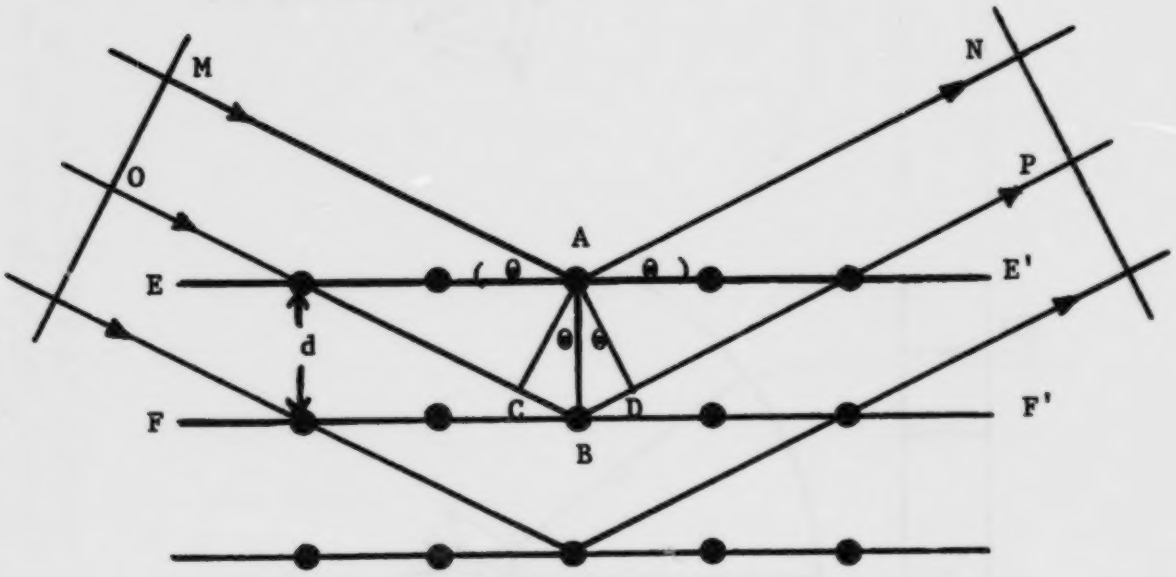


Figure 5. Illustration of the condition for diffraction according to the Bragg equation. Path difference CB + BD = 2d sin θ and this must be an integral number of wavelengths.

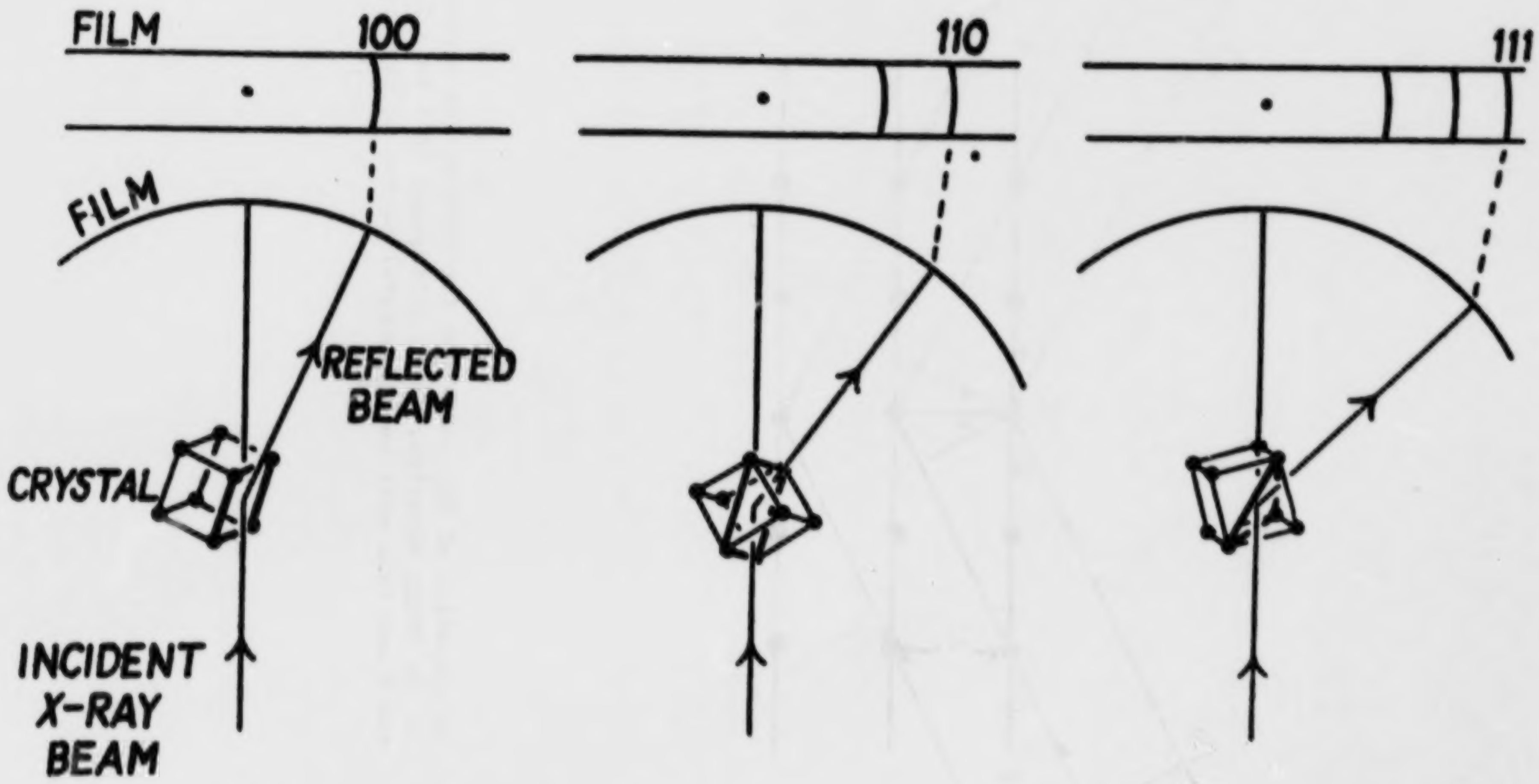


Figure 6. The arcs of x-ray powder patterns originate from "reflections" by particular crystal planes. (From C.W. Bunn, Chemical Crystallography, 2nd ed., p126, with permission from the Clarendon Press, Oxford).

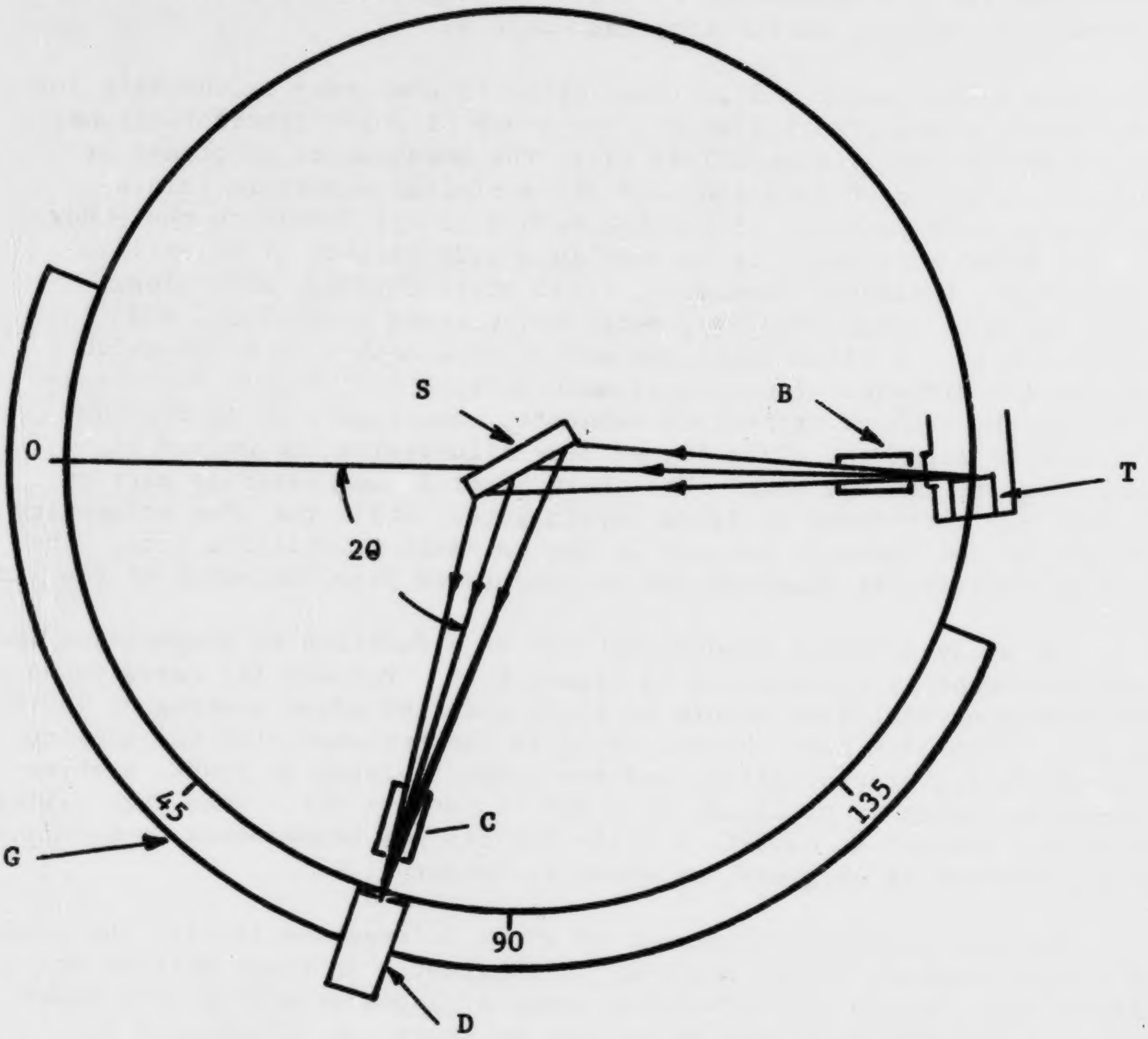


Figure 7. Schematic diagram of x-ray diffractometer. T, x-ray tube target; B & C, slit and collimator assemblies; S, sample holder; D, x-ray detector; G, goniometer scale graduated in degrees.

collimator and slits at B to the sample at S. The diffracted x rays are measured by the electronic detector D which traverses a circular path along the diffractometer circle. The angle 2Θ at which a line is observed is measured on the circular scale G.

This x-ray powder diffraction method is used very extensively for compound or phase identification, the study of phase transformations, the determination of crystallite size, the measurement of stress or strain, preferred orientation, and other similar structure-related properties of materials. Since the method is applicable to the study of most solid materials, it is used in a wide variety of scientific disciplines, including chemistry, solid state physics, mineralogy, ceramics, metallurgy, biology, medicine, polymer technology, and others. Figure 8 illustrates the use of this method to distinguish between two different forms of alumina hydrate.(1) Figure 8a corresponds to the alumina tryhydrate bayerite, and figure 8b is for the monohydrate boehmite. This figure also illustrates the method of measuring crystallite size. The sharp lines in the bayerite pattern (figure 8a) correspond to large crystallites, while the line broadening evident in the boehmite pattern is due to small crystallite size. The average crystallite diameter can be calculated from the width of the lines.

The study of phase transformations as a function of composition and heat treatment is illustrated in figure 9.(2) Pattern (a) corresponds to the poorly crystallized γ-form of Al_2O_3 obtained after heating at 750°C in air. When 19.6 mole percent Cr_2O_3 is incorporated with the alumina hydrate during precipitation, and the product heated at 750°C, a three-component system is obtained, as shown in pattern (b). When this mixture is heated further at 1400°C, a well-crystallized homogeneous Cr_2O_3-Al_2O_3 solid solution is obtained, as shown in pattern (c).

The most powerful techniques of x-ray diffraction involve the study of single crystals of the material of interest. In these methods the diffraction pattern consists of an array of spots resulting from beams that are diffracted in many directions in space, as illustrated in figure 10. These patterns are conveniently recorded on a cylindrical film surrounding the crystal, and a typical pattern is shown in figure 11. The essential information to be obtained from these patterns is the position and intensity of each reflection, and it is desirable the measure the intensities as accurately as possible. This is done most satisfactorily by electronic methods, but in order to measure all of the reflections it is necessary for the detector to scan over a cylindrical or spherical surface rather than in just one plane, as in the powder method. Special diffractometers have been designed for this purpose, and as will be pointed out by other speakers on the program, the requirements of greater flexibility in operation also introduce some additional problems of shielding against scattered radiation.

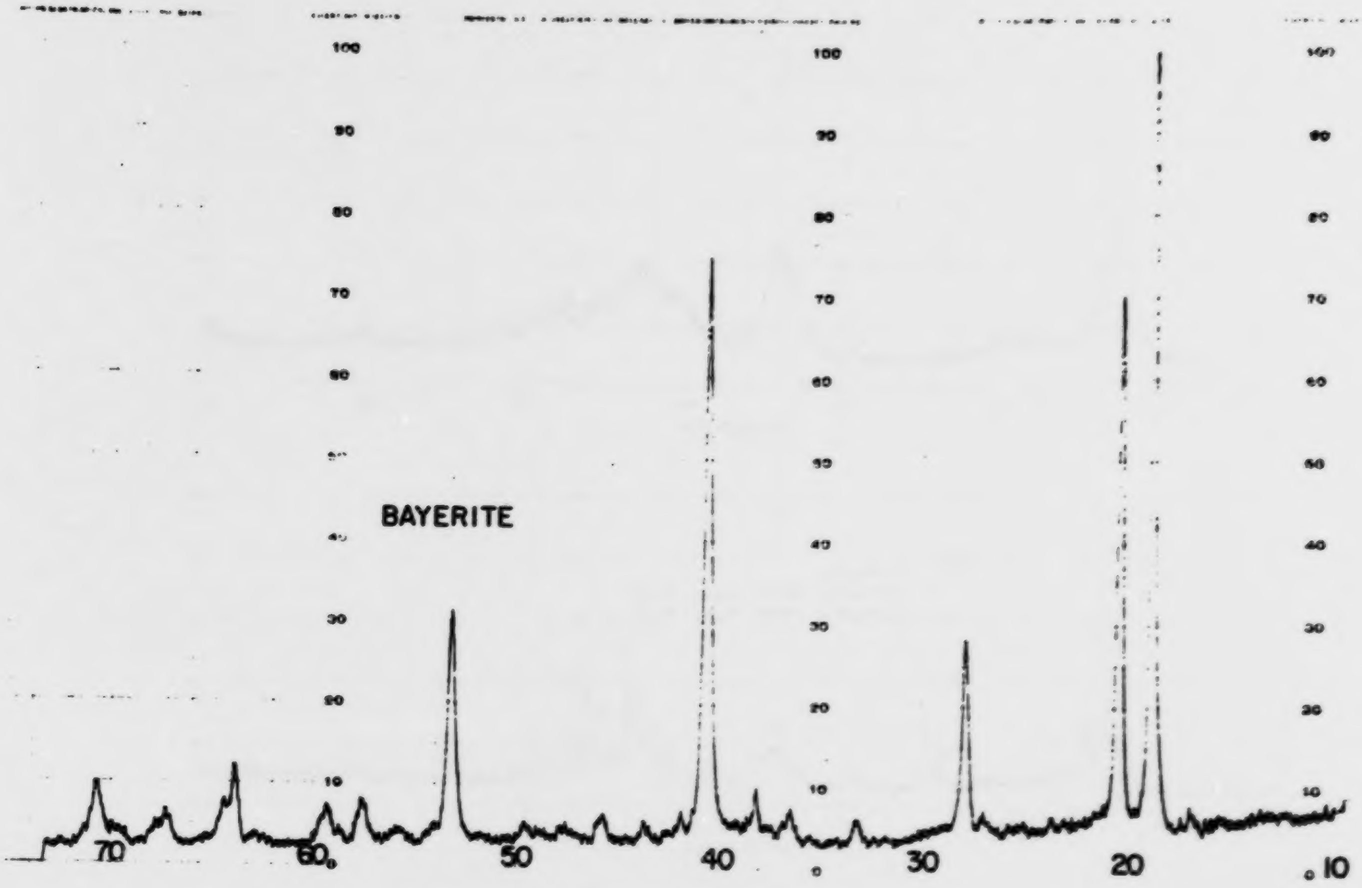


Figure 8a. Bayerite ($Al_2O_3 . 3H_2O$)

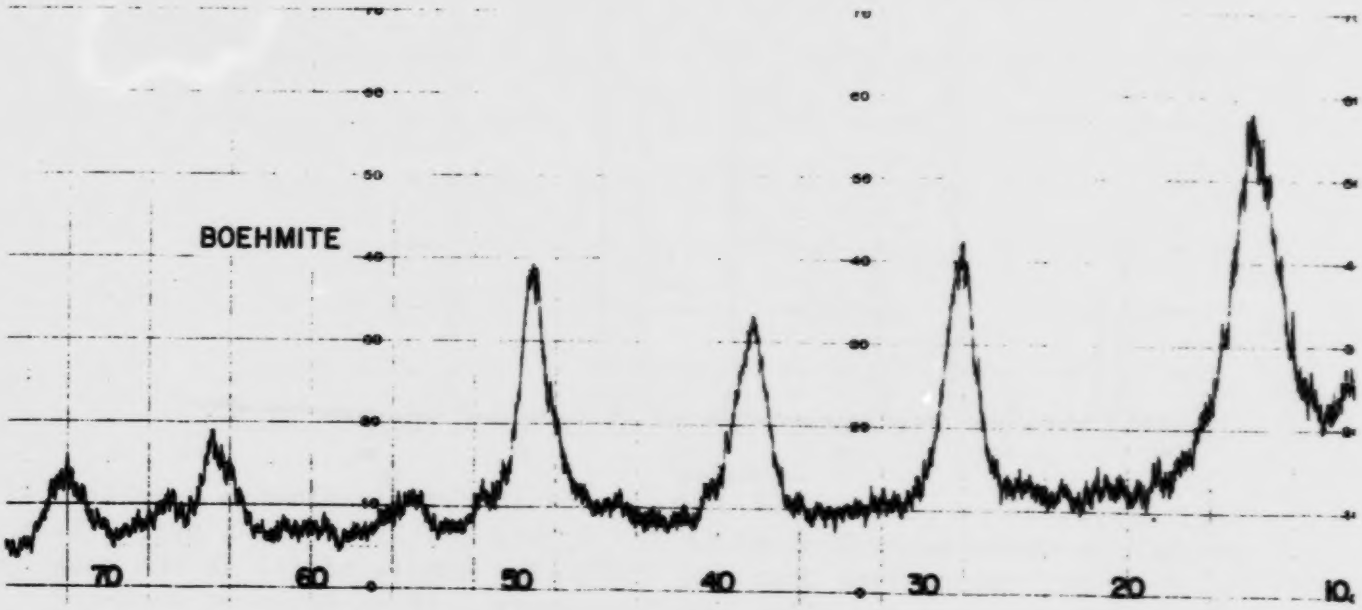


Figure 8b. Boehmite ($Al_2O_3 . H_2O$)

Figure 8. X-ray diffraction patterns of two alumina hydrates.

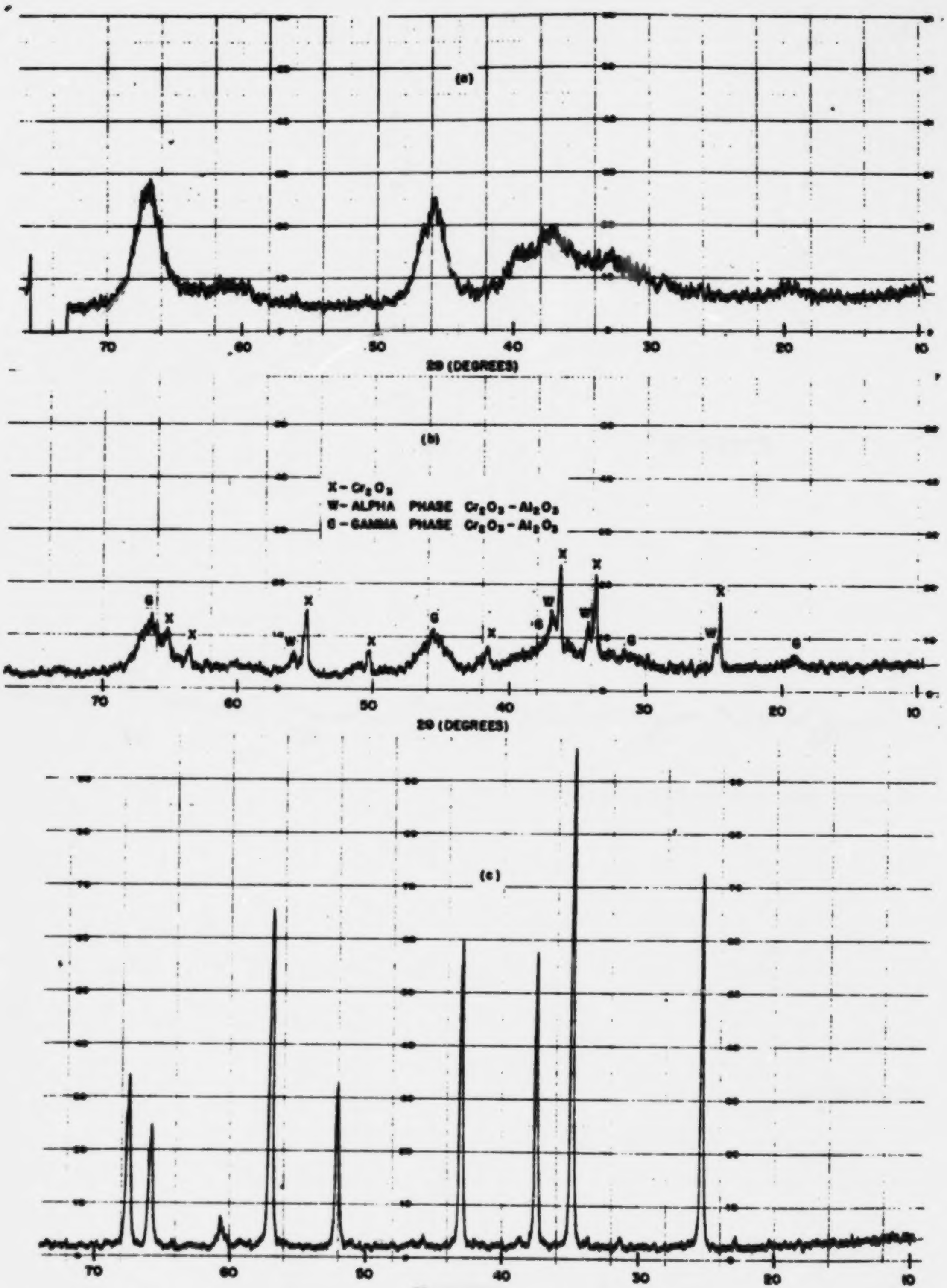


Figure 9. X-ray diffraction patterns of coprecipitated chromia-alumina samples containing chromium equivalent to (a) 0, and (b) 19.6 mole % Cr_2O_3, both calcined for twenty-four hours at 750°C. The sample of (c) is the same as for (b), but heated at 1400°C for five hours. (From Advances in X-ray Analysis, Vol.4, p117, (1961), with permission from the Plenum Publishing Corp.)

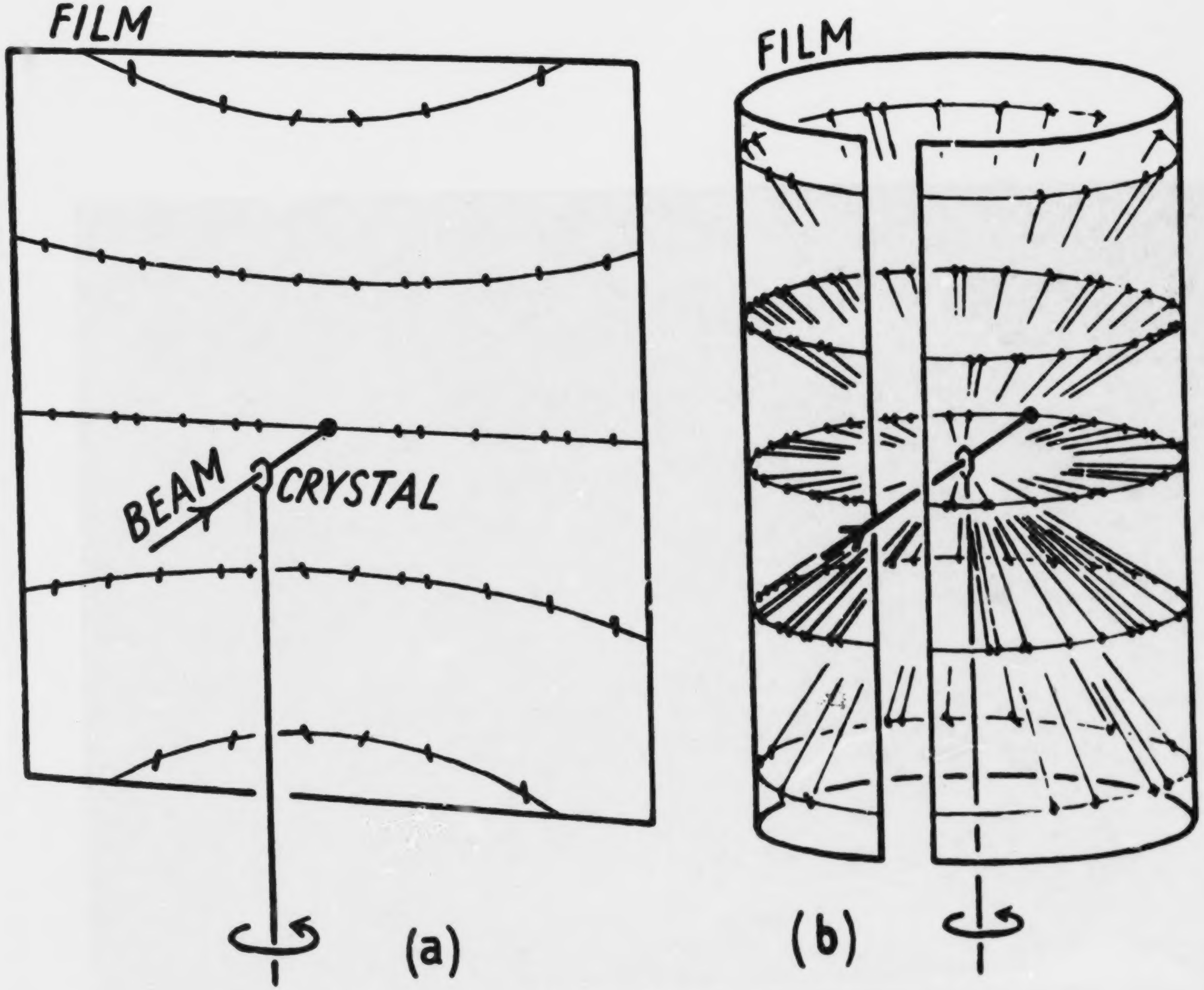


Figure 10. Arrangements for taking single-crystal rotation photographs (a) on flat films (b) on cylindrical films. (From C. W. Bunn, Chemical Crystallography, 2nd ed., p148, with permission from the Clarendon Press, Oxford)

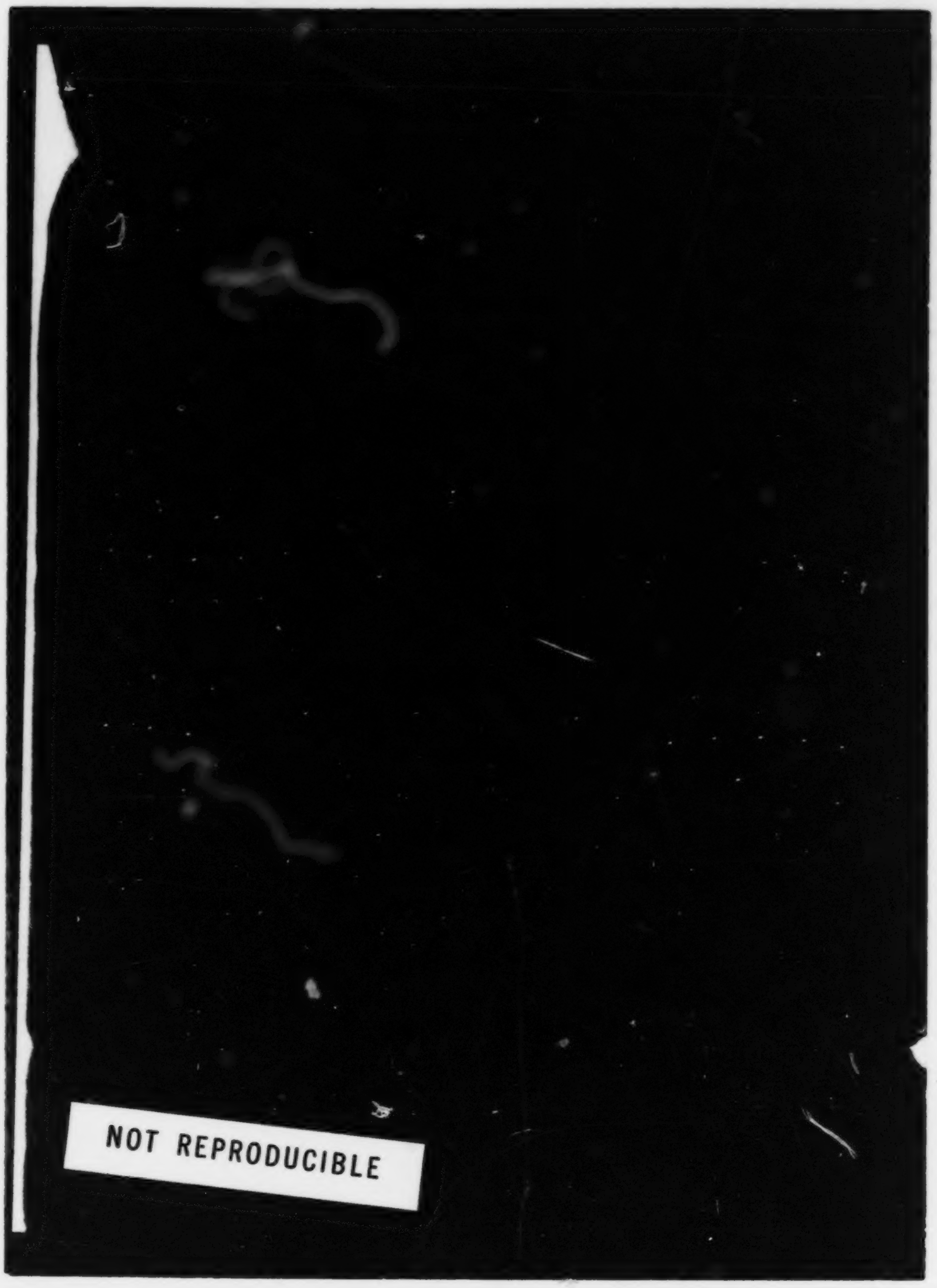


Figure 11. Zero-layer Weissenberg photograph of brewsterite, an aluminum silicate mineral. (Courtesy of A. J. Perrotta).

Fluorescent X-ray Spectroscopy

This is an analytical method for determining the elemental composition of a sample. The sample is irradiated with a high-intensity x-ray beam which excites the characteristic x-ray spectrum of each atom in the sample, as indicated previously. The spectrum of x rays emitted from the sample may be analyzed either in a nondispersive method by means of an energy-sensitive detector, or by the dispersive method in which a single crystal in an x-ray diffractometer is used to separate and record the wavelengths present. The latter method is shown schematically in figure 12, and a typical spectrum is shown in figure 13. High intensity beams of fairly penetrating radiation are utilized in this method, and in order to minimize the hazards from scattered radiation, the instruments are usually completely enclosed. This is not difficult to accomplish because of the relatively simple geometrical requirements of this method. Access doors are provided for changing samples and analyzer crystals, and these doors are equipped with safety interlocks to prevent accidental access to the x-ray beam.

Types of Personnel Involved with Analytical X-ray Equipment

X-ray diffraction and fluorescent x-ray spectroscopy are utilized extensively in colleges, universities, and commercial laboratories of all kinds. In colleges and universities large numbers of students with no previous knowledge or experience with x rays use the instruments in the laboratory courses, and an important part of the training should consist of making them aware of the potential hazards of the x-ray radiation. At the graduate level the applications of x-ray diffraction usually are at a higher level of sophistication, and the student should be in a better position to understand and appreciate the problems associated with adequate protection from scattered radiation. It is also true that the hazards from scattered radiation may be greater from the unconventional apparatus that often is set up for thesis work.

In commercial laboratories the applications range from routine-type powder diffraction and spectroscopic analysis to the more sophisticated applications which require single crystal techniques or special instrumentation designed to study materials at high or low temperatures, high pressures, and sometimes in controlled atmospheres. Bulky or odd-shaped samples also must be accommodated in some applications. It is imperative that technicians carrying out the more routine applications work under the supervision of a person who is qualified to train them in safe operating procedures; the more sophisticated non-routine applications of x-ray difraction must be carried out by personnel with an adequately higher level of training and experience. The equipment that is used must incorporate safety devices that will prevent access to the area of the primary or scattered x-ray beams when the x-ray tube is energized.

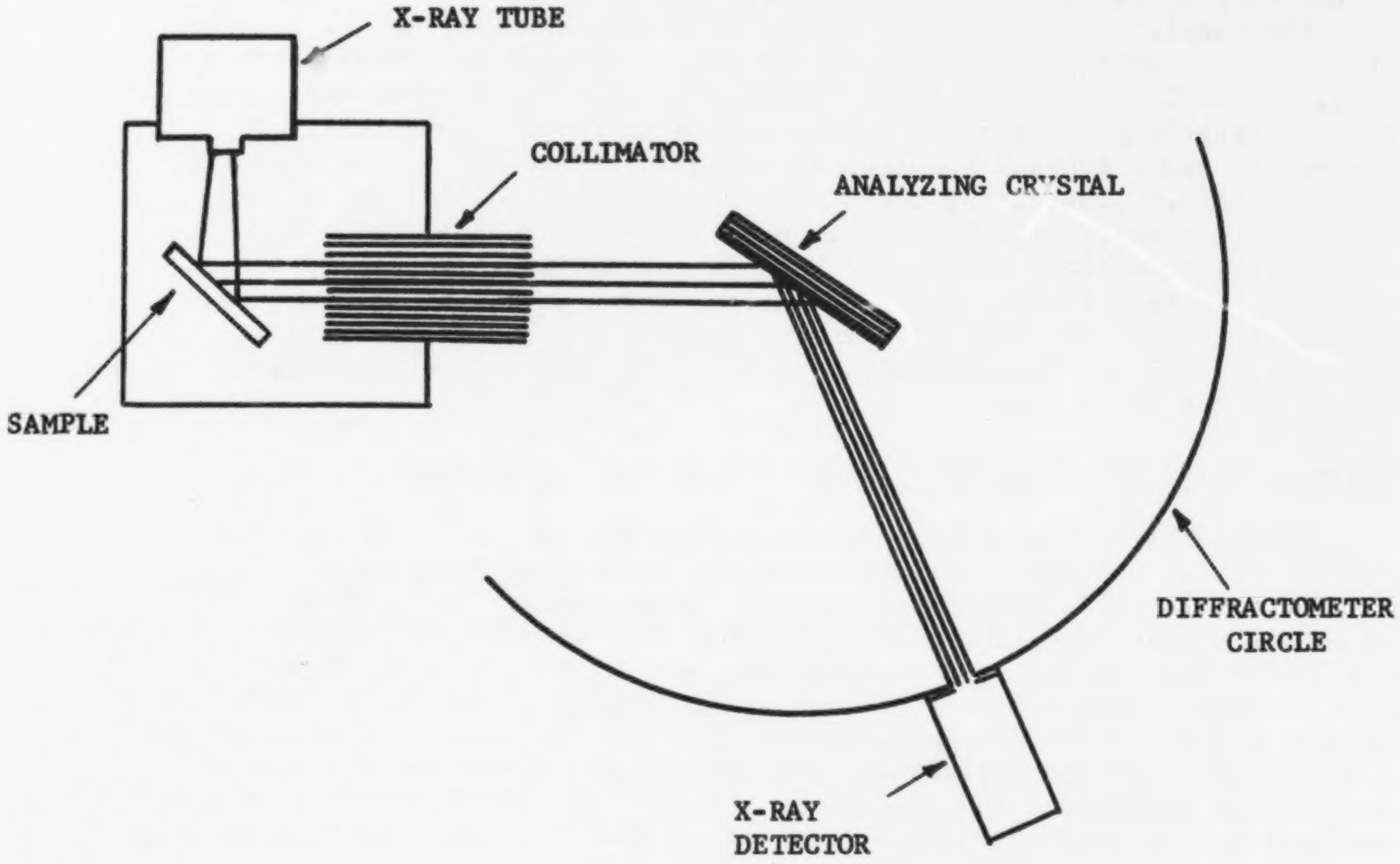


Figure 12. Schematic diagram of fluorescent x-ray spectrometer (dispersive method).

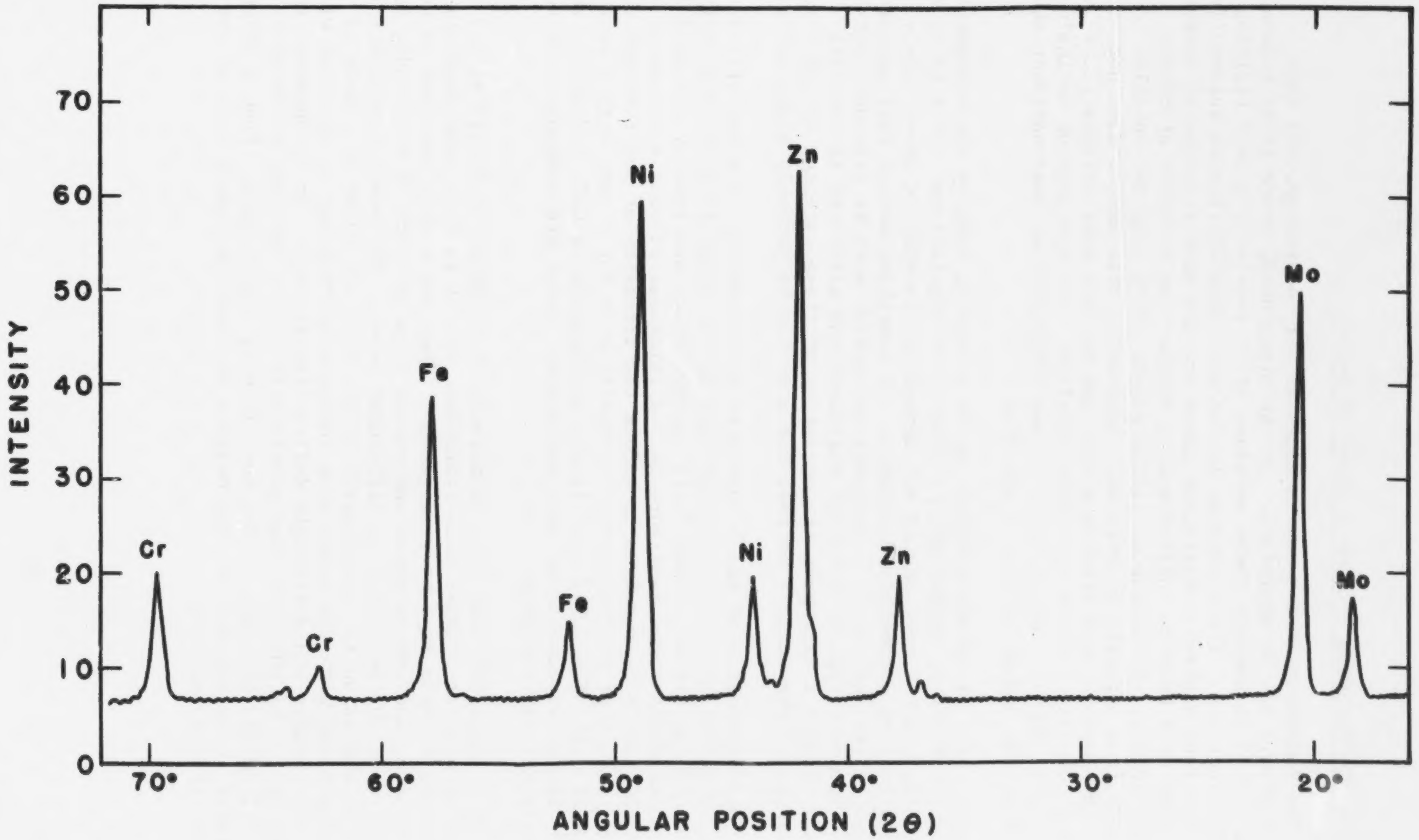


Figure-13. Fluorescent x-ray spectrum from a sample containing Mo, Zn, Ni, Fe, and Cr.

Hazards of Operating Machine Sources of X-rays

The radiation from x-ray machines is very dangerous, and such danger should not be minimized. On the other hand, there is no reason to be afraid to operate these machines after receiving proper training and instructions. The situation is somewhat like driving an automobile on a two-lane highway. Certainly there are few more frightening dangers than that of a head-on collision with another car or truck at normal highway speeds, but this possibility exists every time two vehicles approach from opposite directions. Apparently this danger does not deter many people from driving a car, and in fact most drivers probably are too complacent about the risks involved. The operator of an analytical x-ray machine should never become complacent or overconfident about the potential danger from an x-ray beam.

All sorts of safety devices may be provided, both by the equipment manufacturer and by government or laboratory regulations. This is as it should be, but the user should not depend too heavily on these safety devices lest he become overconfident. If something should fail unnoticed, serious injury may result. Adequate safeguards must be provided, but these can never replace constant vigilance and alertness to possible danger. Proper training in the operation of these machines should teach the nature of the hazards so that the user can be properly alert and vigilant.

The wavelengths of the x rays used most commonly in x-ray diffraction and fluorescent x-ray spectroscopy fall in the range from approximately 0.5 to 10Å. These are so-called "soft" x rays which are readily absorbed in matter, as illustrated in figure 14. A thickness of only a few mm or less of Al, Fe, or Pb is required to reduce the intensity of the transmitted beam to 1/10 that of the initial intensity even for x rays with a wavelength of 0.5Å. The 1.54Å wavelength corresponds to CuKα radiation, and 1.93Å is the wavelength of FeKα radiation. These are commonly used sources in x-ray diffraction work.

It is apparent that only relatively thin layers of shielding are required to protect against this radiation, but it is this same property that makes these x rays very dangerous. They are highly absorbed in even soft tissue, and severe burns can result from exposure of the hands, arms, skin or eyes to the direct or diffracted beams. The maximum permissible doses of radiation for these parts of the body are shown in figure 15 for comparison with the x-ray beam intensities that may be obtained with high-power tubes and a strongly diffracting crystal. It is apparent that a dose of 100 to 500 times the permissible yearly dose may be obtained from a 1-second exposure to the most intense direct beam. Even a strong diffracted beam can deliver the maximum permissible yearly dose to the eye in less than 10 minutes.

Figure 14

THICKNESS, IN CM, OF ABSORBER REQUIRED TO REDUCE THE INTENSITY OF THE TRANSMITTED X-RAY BEAM TO 1/10 THAT OF THE INITIAL INTENSITY

	1.93Å	1.54Å	0.9Å	0.5Å
Air	80	165	770	3300
Al	0.009	0.017	0.08	0.46
Fe	0.004	0.0009*	0.004	0.21
Pb	0.0005	0.0009	0.0014	0.004

* FLUORESCENT RADIATION EXCITED

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Figure 15

MAXIMUM PERMISSIBLE DOSES OF RADIATION

WHOLE BODY, HEAD and TRUNK, ACTIVE BLOOD FORMING ORGANS, GONADS, OR LENS OF EYE	5(N-18) REM/YR.
SKIN, THYROID, and BONE	30 REM/YR.
HANDS, ANKLES, FOREARMS and FEET	75 REM/YR.
OTHER ORGANS	15 REM/YR.

(N is age in years)

X-RAY BEAM INTENSITIES

PRIMARY BEAM:	400,000 R/MIN.
DIFFRACTED BEAM:	80 R/HR. (MAX.)

(BEAMS MAY BE VERY SMALL IN CROSS-SECTION)

The principal sources of hazardous radiation from x-ray diffraction and fluorescent x-ray spectroscopic equipment are listed in figure 16. It should be noted that in x-ray diffraction both the primary beam and the diffracted beams are small and well collimated, which increases the possibility of receiving severe burns on very localized areas of the fingers, hands, eyes, or arms if inadvertently exposed. Leakage of the primary beam or scattered radiation through cracks or small openings in the shielding likewise may give rise to small but intense beams which may escape detection in general area radiation surveys unless the survey is carried out carefully. The penetration of the primary beam through shutters on commercial equipment may result if the shutter becomes defective or does not close properly. Improperly designed shielding can itself be a hazard if it is excited to fluorescence and the radiation is allowed to scatter into the room. The rectifiers in the high-voltage power supply constitute a frequently unsuspected source of hazardous radiation. When they become gassy they function like x-ray tubes, and due to the high voltages that may be impressed across them, they can emit penetrating radiation. It is essential that adequate shielding be provided around the rectifier tubes to prevent this radiation from escaping into the room.

Precautionary Measures

A suggested list of general precautionary measures to be taken to protect against accidental exposure to x radiation is shown in figure 17. To be effective, the shielding must prevent any stray radiation from escaping into areas where it can be intercepted by personnel in the room. Care should be taken to avoid cracks or small openings which may go unnoticed.

Tube status indicators should be provided both at the on-off switch and near the tube head so that the operator will be reminded whenever the x-ray beam is on. In addition, a light or other signal should be provided to indicate when the shutter is open, and this should be augmented by interlock switches or manual control devices that will prevent access to the beam area when the shutter is open. It is advisable to conduct a regular maintenance program scheduled and checked by a responsible person other than the operator in order to insure that these safety devices are always in proper working order.

Radiation monitoring is of two types. On the one hand, the intent is to determine how much radiation a person may have received in a given period of time. For this purpose a film badge is worn, but this usually indicates only the general level of radiation in the room, or the level of whole-body radiation. For analytical x-ray machines it is preferable to supplement this with a finger badge, or even a wrist badge, to indicate when the fingers or a hand may have been irradiated accidentally.

Figure 16

SOURCES OF HAZARDOUS RADIATION

1. PRIMARY BEAM
2. LEAKAGE OF PRIMARY BEAM THROUGH CRACKS IN SHIELDING
3. PENETRATION OF PRIMARY BEAM THROUGH SHUTTERS, ETC.
4. SECONDARY EMISSION FROM SAMPLE OR SHIELDING MATERIAL
5. DIFFRACTED RAYS
6. RADIATION GENERATED BY RECTIFIERS IN THE HIGH VOLTAGE POWER SUPPLY

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Figure 17

PRECAUTIONARY MEASURES

1. EFFECTIVE SHIELDING
2. TUBE STATUS INDICATORS
3. INTERLOCK SWITCHES
4. RADIATION MONITORING
    a. FILM BADGES
    b. RADIATION SURVEYS
5. HEALTH SURVEILLANCE
    a. EYE, SKIN, AND FINGER NAILS

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Radiation surveys in the area around the tube head and associated equipment are conducted to check the adequacy of the shielding. This should be done periodically with a detector which is sensitive to the x-ray wavelengths being used or generated. A survey should also be conducted whenever the geometrical arrangement or design of the equipment is changed in order to accommodate new experiments or procedures.

Conclusion

In the consideration of the potential hazards of radiation and the precautionary measures to be taken to avoid exposure by users of analytical x-ray machines, I have deliberately limited myself to a rather brief general discussion of the factors involved. The various aspects of attaining radiation safety in the use of these x-ray machines will be discussed separately and in detail by the other speakers at this Conference. It has been my purpose simply to provide a general introduction and some background information concerning the nature of the problems to be considered. At this point I will leave the more complete discussion of these problems to the other speakers.

References

(1) W. L. Kehl and M. M. Stewart, Gulf Research & Development Co., unpublished data, December, 1961.

(2) W. L. Kehl, "A Technique For Studying Coprecipitated Chromia-Alumina Catalysts by X-ray Diffraction", in Advances in X-ray Analysis, Vol. 4, pp117-129, Plenum Press, New York, (1961).

DISCUSSION

WARREN INGLES (Frankford Arsenal): About 15 years ago I think I was involved in a session similar to the one you have here in industrial x rays. So, I would like to ask the speaker a question.

You spoke about training some of your students. If I, as a stranger, walked in, how would I know that student was trained? Do you give him a card?

Secondly, assuming that this somebody is hurt later, is there anything to identify the responsible supervisor who okayed his using the equipment?

DR. KEHL: I can speak only from the point of view of the industrial user. The way we operate, my equipment is under my supervision, and I am responsible for its operation. The way I cope with the problem of potential hazards from operation of the equipment by improperly trained personnel is to have only one or two trained people who are authorized to use the equipment. And, in fact, they are the only two people who are authorized to go into the room where this equipment is being used.

MR. INGLES: Let me say this. I believe Gulf probably has x-ray radiographic systems in operation. I would imagine, as such, that they use the qualification procedures of the Society for Nondestructive Testing. What I was trying to imply is that out of a series of meetings here in a couple of years may come some similar procedures.

DR. KEHL: I am not certain whether or not I understand your question. We have multiple installations in our laboratory and we have a Radiation Safety Committee to oversee all these installations. These are the people who are overseeing things, but each unit is in a particular department under the responsibility of a given supervisor. That supervisor has the responsibility for seeing that the equipment is used properly and safely. The Radiation Safety Committee attempts to insure that everybody observes not only the government standards but also the company standards. In fact, I think that the company standards are, in some respects, more severe than the government standards and recommendations.

Does that answer your question?

MR. INGLES: In part. What I am trying to say, I believe, is that there are certain standards that all companies today are taking in industrial radiographic safety. I have a feeling that this group eventually wants to come to certain minimum levels.

For example, you may train a man for 1 hour and put him on a machine.

DR. KEHL: No.

MR. INGLES: Wait a minute. You may. Another company may train him for 5 years and put him on a machine. Being familiar with the things at Gulf and Aerojet, and so forth, across the country, I have a great appreciation that the training and the method of documenting it has varied very considerably up to the past 2 years.

DR. KEHL: That probably is quite correct.

MR. INGLES: Now there is a standard that certain societies are using. The thought behind it or the philosophy behind it, one of the things that I would suggest possibly is that everybody here today put in their own words their own positions, what they feel are minimum protection barricades, minimum ways of identifying that the interlocks are or are not working, how often monitoring takes place, some of these things, in order that maybe 3 years from now you may be able to pick all the minimums of everybody concerned.

DR. KEHL: There is a point that I actually had intended to make in my talk, but I forgot it. In **smaller** laboratories where the number of scientifically trained persons is limited, there may be a problem in that there is no well-trained x-ray specialist on the staff, but the laboratory wants to do x-ray work. So, they select someone from the group and try to get him trained to do the job. If the training this person receives is directed mainly toward the applications of x-ray methods, he may not be made fully aware of the potential dangers of using analytical x-ray equipment, and the risk of accidental exposure to radiation is increased.

In the larger organizations I think this problem is not so serious because there usually are enough qualified people around who can supervise work of this kind and minimize the risks of exposure to radiation.

THE ACUTE AND CHRONIC EFFECTS OF IONIZING RADIATION ON SKIN (RADIOBIOLOGIC AND MEDICAL CONSIDERATIONS)

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Temple University, School of Medicine
Skin and Cancer Hospital
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RADIOBIOLOGIC CONSIDERATIONS

P. Donald Forbes

The aim of this paper is to point out some of the radiobiologic events following the absorption of radiation by a tissue. In discussing this, we need to investigate a broad spectrum of radiation because in the particular application that we have in mind there are few directly available and directly applicable quantitative data. Consequently, I will be talking in terms not only of x-ray radiation in the range of 30 to 50 keV, but also the Grenz-ray region of 10 to 20 to 30 keV, and beta radiation as well.

I. ENERGY ABSORPTION

It has already been pointed out that radiation of the energies that we are considering is highly absorbed in material, including tissue. While figure 1 stresses the less energetic radiations, with energies of 6 to 12 keV, it is also true that even into the range of 50 keV the photons will be absorbed primarily within the first few millimeters of tissue. That "first few millimeters" of tissue is mostly skin, although in certain areas of the body, notably the extremities, it can also include some bone.

The way that the energy is absorbed can get very complex, both because of the nature of the radiation and the nature of the absorbing material. Figure 2 indicates that some of the radiation will be directly reflected from the surface. What we have sketched here is, in relative size, the depth of epidermis, including a dead superficial layer of stratum corneum (which is not indicated separately), a layer of epidermis and a layer of dermis below. The epidermis, as I will point out, contains the epithelial regenerative component of skin and the dermis the connective tissue and vascular supply of the superficial part of the skin.

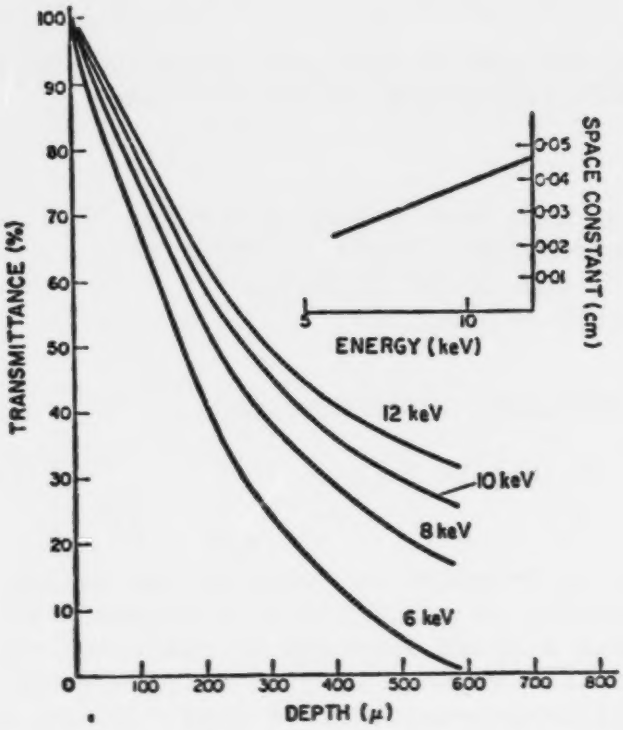

Figure 1. Transmission of Grenz x-rays through skin. (R. T. Tregear, Physical Functions of Skin, © 1966. Reprinted by permission of Academic Press, Inc., N.Y.)

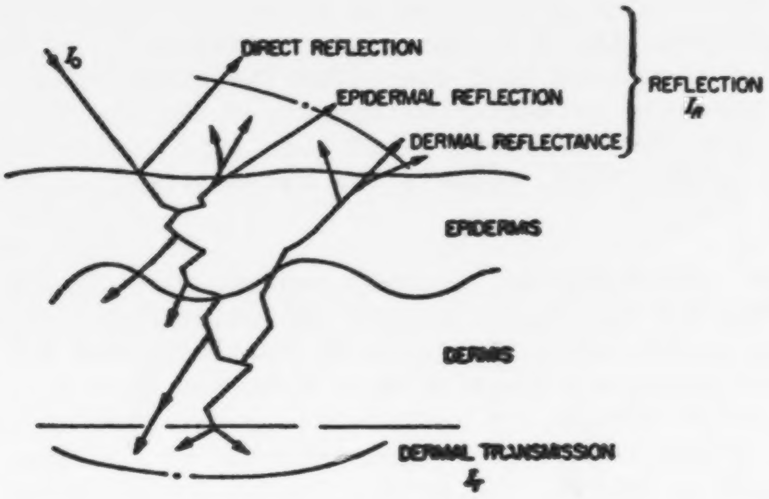

Figure 2. Reflection and transmission in skin. (R. T. Tregear, Physical Functions of Skin © 1966. Reprinted by permission of Academic Press, Inc., N.Y.)

In any case, the radiation can be directly reflected from the surface and, therefore, have no effect on the skin, or it may be scattered within the medium of the epidermis or the dermis, and reflected back or later absorbed, or any of the number of possibilities. These lead to problems of interpretation of dosimetry in particular; but, in any case, we are dealing with radiation which is largely absorbed in the superficial parts of the tissue.

II. STRUCTURE OF SKIN

We will think now for a moment about the structure with which we are most directly concerned; that is the organ called skin (fig. 3). We do not want to forget that the eye and other portions of the body's surface can come in contact with "soft" radiation. But the skin, of course, is the one with which we are most directly concerned at the moment. I mentioned the stratum corneum, the dead overlying products. The epidermis itself is called a layered regenerative tissue, because the lowermost or basal layer of the epidermis shows very high mitotic activity and is constantly replacing the cells which are lost to the surface. Immediately below that is the body of the skin proper, the dermis, containing blood vessels, both those which course through the dermis and those which supply the nutritional need of the epidermis, the epidermis itself not being vascularized.

Not only the outer layer of living cells, the living and connective tissue portion, but also extensions of the epidermis go down into the dermis, notably such organ structures as hair follicles and their associated sebaceous glands, muscles associated with the hair follicles and sweat glands, which are also extensions of the epidermis. What should probably be pointed out here is that the first few millimeters of tissue down to about halfway into the length of the hair follicle will be that portion which will absorb very heavily in the region of 10 to 50 keV.

Among the various tissues of the body, this particular part, the epidermis (fig. 4), is among the most sensitive indicators of radiation damage. Its kinetics are very radically upset by even relatively small doses of radiation; using appropriate techniques, this makes a very interesting system for evaluating the radiation absorbed.

The connective tissue, as a whole, is less sensitive, probably largely based on the fact that its turnover time is much longer. In any case, this connective tissue component has within it the blood vessel supply, which is not as easily recognized in this preparation (fig. 4) as it is in a drawing. Note the blood vessels in the area immediately below the epidermis. In recognizing radiation damage, it is those blood vessels which give us some of the first indicators of the fact that exposure has occurred. If we specially prepare such a biopsy so that we

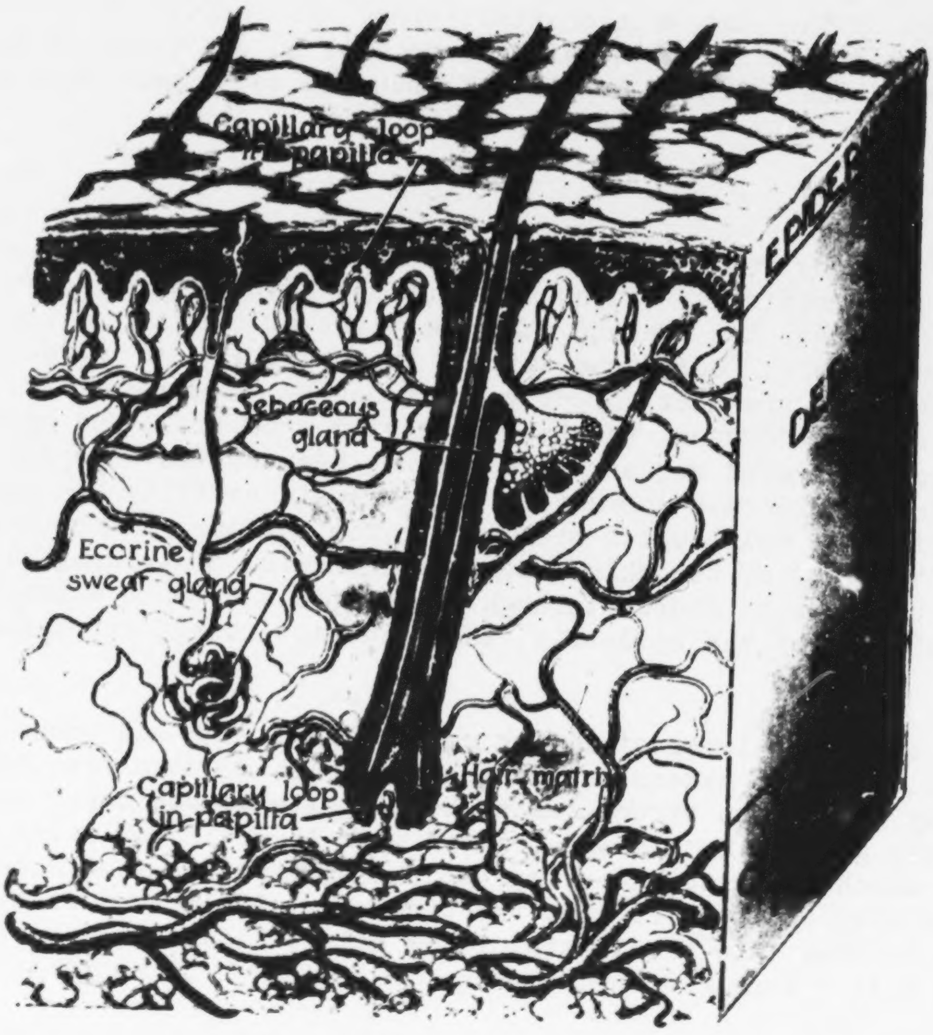

Figure 3. The skin.

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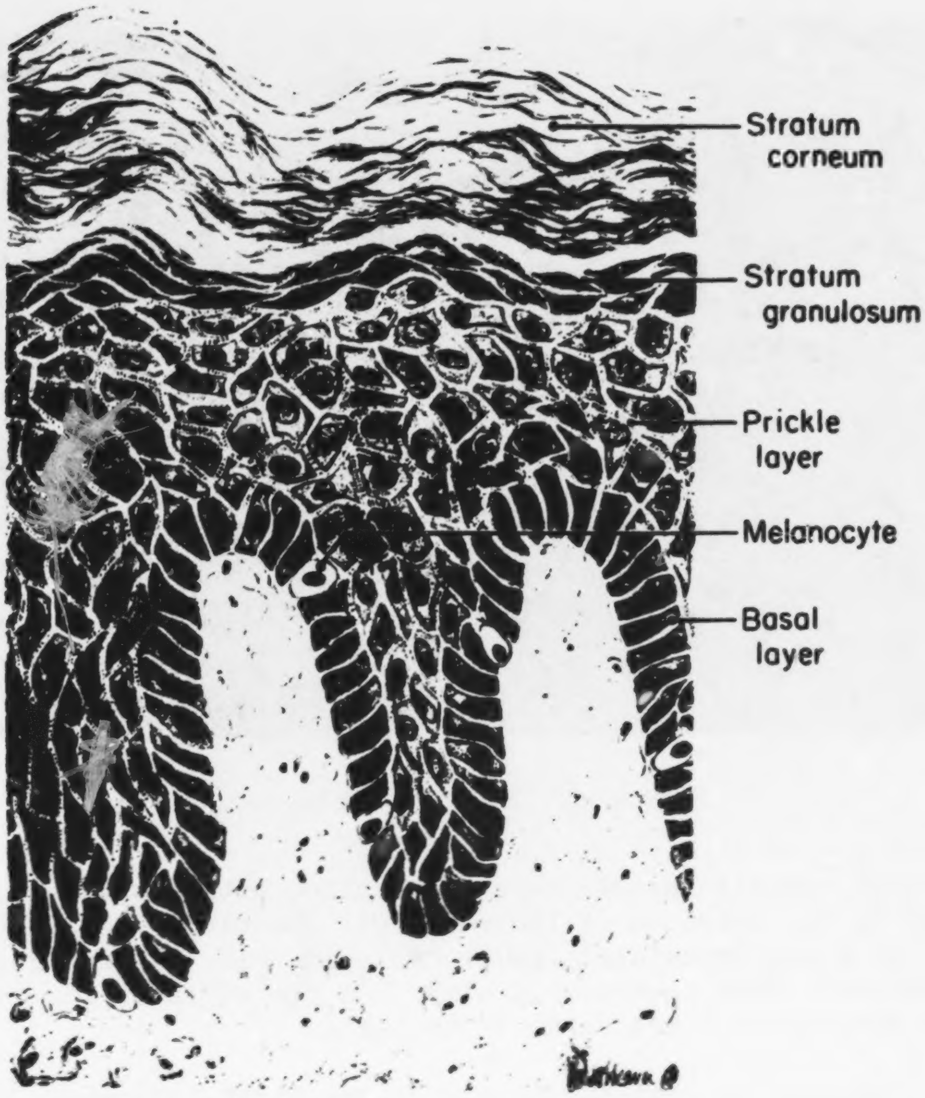

Figure 4. The epidermis.

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can visualize where these blood vessels are, the appearance is somewhat as we see it in figure 5.

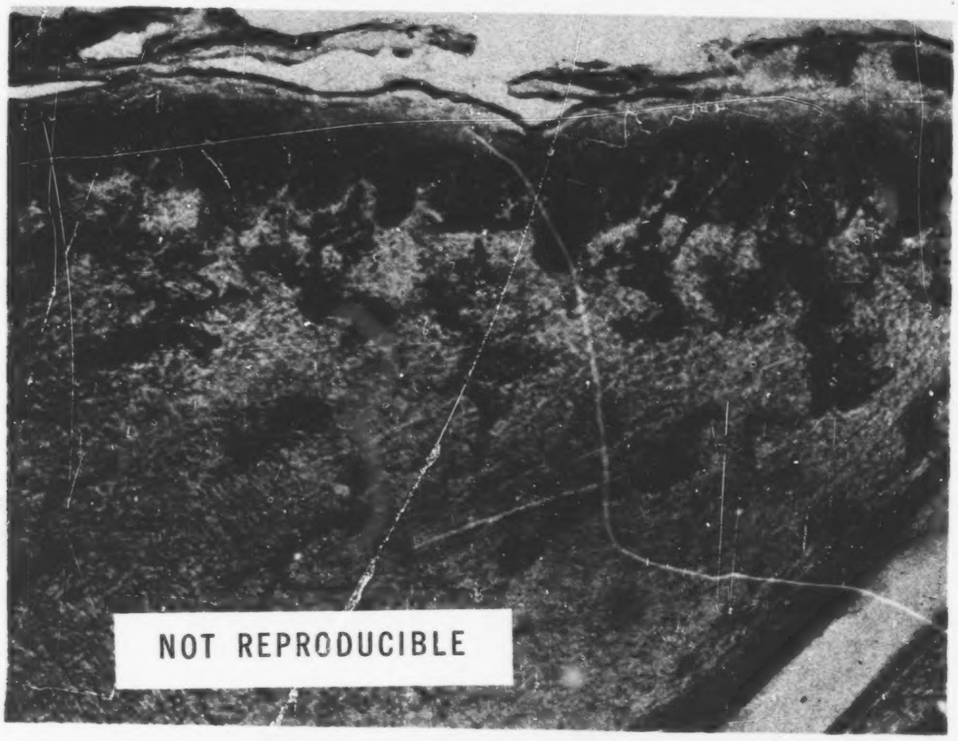

Figure 5. Blood vessels.

The blood vessels in this case are stained with a special material which shows us the location of the vessels. The blood vessels in question are those which are immediately below the epidermis. These vessels have marked dilation. They increase in size. On the surface, the change that this makes visible is a reddening of the skin.

This reddening or erythema is one of the first indicators of a problem. It can indicate the problem within a few hours after exposure, if the dose is high enough and if the quality of radiation is soft enough. That is, there is a direct relationship between the dose in producing erythema, the shortness of the latent period, and the wavelengths of the radiation in question. Considering the length of time that x-ray and skin and erythema have been around, one would suppose that most of these relationships would be very well known and very well established by this time. As a matter of fact, there is a minimum of actual quantitative data from which one can make judgments in specific cases. I will have a bit more to say about that in a moment.

We are, at the present time, studying the significance of these changes in blood vessels. One of them, which I will point out here just for the sake of interest, is shown in figure 6, which is the cheek pouch of the hamster. It has the advantage that one gets the vessels right out there where one can see them and measure them nondestructively, which is very difficult to do in other living tissues. In any case, this is one place where one can study what is happening radiobiologically after the absorption of various kinds of radiation. An area of congestion is obvious.

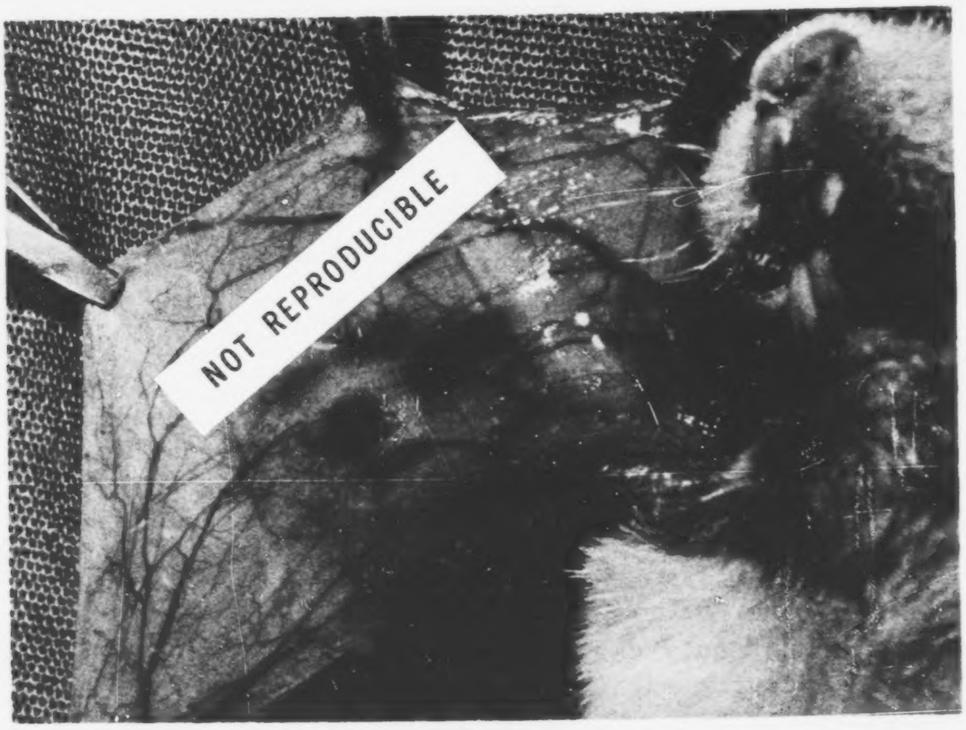

Figure 6. Cheek pouch of hamster.

One of the other changes which occurs fairly soon after radiation exposure is another change in color. This change depends not on blood vessels but upon cells which produce color; namely, pigment cells or melanocytes. These two kinds of changes are shown briefly in figure 7, in terms of their time courses, though I must emphasize that the time courses are influenced by dose and quality of radiation. Erythema resulting from ultraviolet light appears within a few hours to a day or so, again depending on the dose. It peaks rather soon and disappears within a few days. The pigmentation (that is, stimulation of the production of the brown color of skin) increases much more gradually, peaks later, and is more persistent.

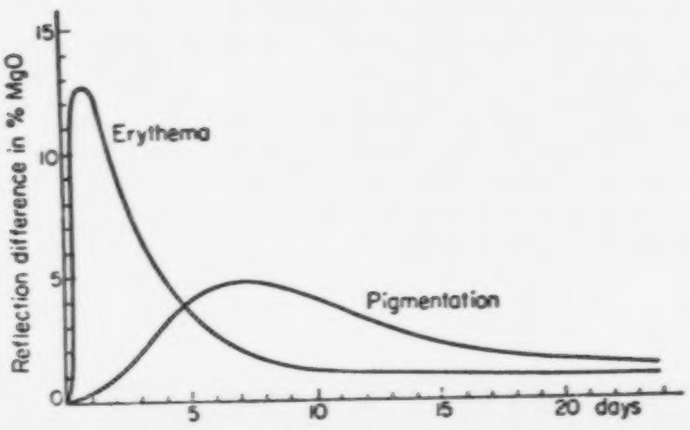

Figure 7. Temporal course of erythema and pigmentation after a 4 MED of ultraviolet light delivered by a hot quartz source. (Adapted from Breit and Kligman.) (Carl P. Swanson, Editor. An Introduction to Photobiology © 1969. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, N.J.)

The erythema that is seen after ionizing radiation differs somewhat from this in that it may appear later, perhaps several days later. One of the most interesting characteristics of it is that it recycles. It appears and disappears with two or three major peaks during the post-exposure weeks. Then for several years, it may appear and disappear spontaneously, or as a result of further stimulation of the skin in some way.

Brown pigmentation not only can be increased by radiation exposure, but may also be decreased with much higher exposure, so that one can see both kinds of change.

The cells that are responsible for the change in brownish pigmentation are, as I said before, melanocytes (fig. 8). The melanocytes are found at the basal layer. Thus, the minute blood vessels, the reproductive cells which regenerate the epidermis, and the melanocytes are at about the same depth in skin.

Melanocytes are branched (dendritic) cells, and they produce a material known as melanin which helps to give the skin its characteristic color. They tend to be increased by doses of radiation in the region of 300 to about 1,200 rads and decrease at much higher single doses. The mechanism for operation of these pigment cells is somewhat complex. Figure 8 indicates that one such cell is connected with many of the basal epithelial (epidermal) cells and provides its pigment granules to those cells, so that pigmentation increases not only in the pigment cell itself, but also in the surrounding cells, as well as in the more superficial cells. In summary, the changes in color are brought about largely on the basis of erythema (reddening) of the skin and, perhaps at the same time or somewhat later, a darkening or browning of the skin as a result of melanocyte activity. Melanocytes become more active and they probably become more numerous, and both of these things contribute to the darkening of the skin.

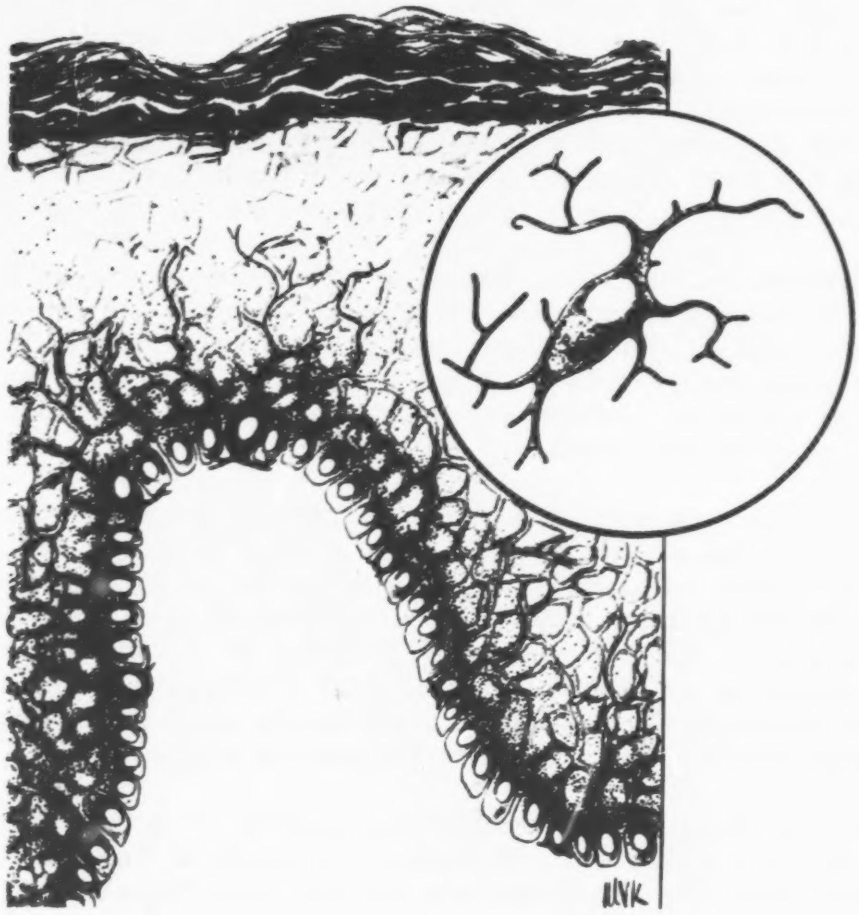

Figure 8. Melanocytes in epidermis.

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What we are considering in this meeting relates to single doses of ionizing and nonionizing radiation. The story becomes quite different, of course, if one is dealing with chronic or fractionated doses, in which one has to take into account not only the differences in the physiologic condition of the tissue at the time, but also recovery factors which play a very large part in the response of tissue. Some parts of the skin can recover rather efficiently, at least by available criteria. Thus, chronic exposures (or fractionated exposures) will affect tissue differently from single exposures.

Cycles of interest in safety have necessarily paralleled engineering developments in the radiation field (i.e., each technology introduces its own set of associated dangers). Historically, distinct sets of biomedical problems were uncovered; for example, with handling of diagnostic machines shortly after the discovery of x rays, with the tolerance of "normal" tissue to x-ray therapy, and with a whole spectrum of effects from military, power generation, and propulsion applications of nuclear energy.

Problem simulation and model building have sometimes been the methods of choice for evaluating magnitudes of several observed or anticipated problems. Microbeams of x rays were developed within the last few years to investigate what the effects of cosmic radiation might be, since very small areas were exposed. These produce quite different effects from equal doses to much larger areas.

Another example that has come under fairly recent investigation is the problem of "hot particles." While this is not directly applicable to the needs of this particular symposium, I think it is of interest to see how one has to begin to investigate a new problem in order to elaborate effective guidelines. The hot particle, whether it is one containing mixed fission products or whether it contains a single radioisotope, introduces special kinds of problems in dosimetry and radiobiology. These are prime considerations in terms of establishing regulations.

In figure 9 we have represented a microsphere of 300 microns diameter and one of 80 microns diameter. Epidermis is shown at the same scale. The "twigs" represent the blood vessels to the superficial part of the dermis.

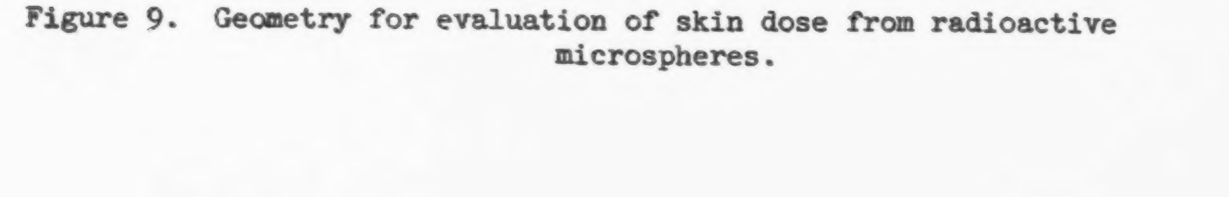

Figure 9. Geometry for evaluation of skin dose from radioactive microspheres.

From any hot particle, it is possible to calculate the dose immediately below that particle and its relationship to the size and intensity of radiation coming from the particle on the surface of the skin. However, the radiation absorbed at any given distance from the particle (e.g., 4 millimeters) is going to be influenced not only by the size of the particle and the fact that there will be absorption of the radiation previous to that point, but also by the configuration of the skin itself, whether it is flat on the surface, or thrown up into folds and creases in skin. This raises problems of dosimetry in trying to identify the critical targets. In trying to evaluate this specific problem, we have used both mice and swine as experimental tools. Figure 10 shows results of this sort of experimentation. The ^{90}Sr silicate particle was on the skin for 7 hours, and one sees erythema has developed as soon as particles are removed from the skin. Progressively, darkening occurs, the increased pigmentation in the area receiving the large dose of radiation and progressing through the development of the depth of epidermis, the sloughing of the tissue, the development of an open ulcer and, finally, over several month's time a greatly protracted healing of that particular region.

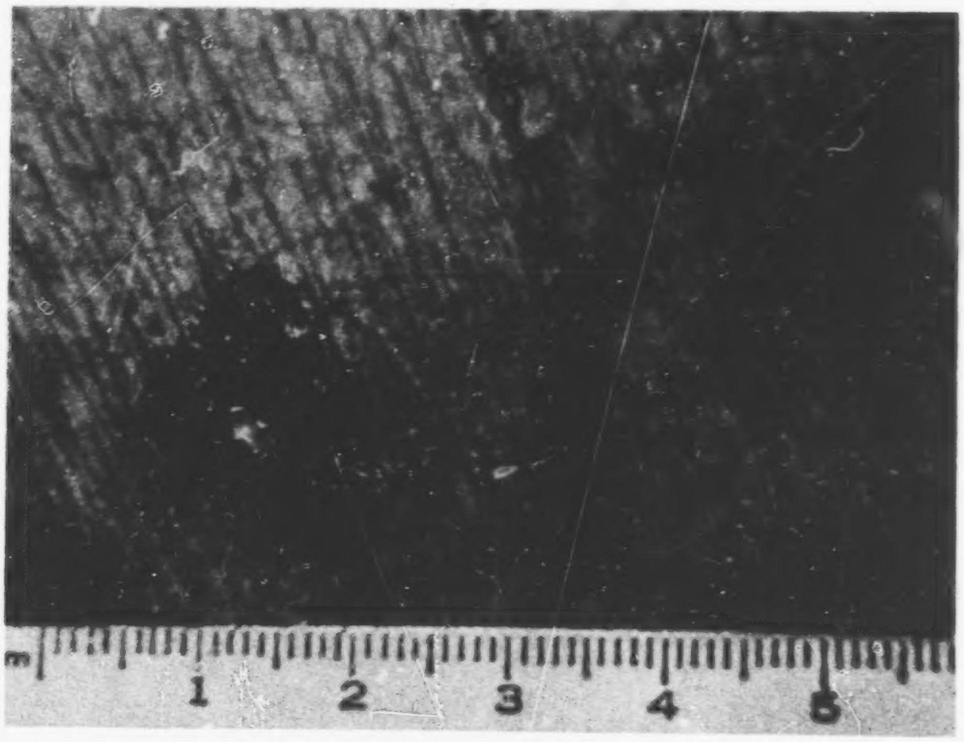

Figure 10. Effect on skin of 7-hour contact with ^{90}Sr silicate particle.

NOT REPRODUCIBLE

We have considered acute changes which include erythema, a type of blistering and ulceration, and pigmentation, which can occur as a result of radiation effects. Late effects must be anticipated but because of the very long latent period of development (perhaps 20 to 30 years in the human) they are much more difficult to evaluate.

In conclusion, while a great deal of information is available on what happens in tissue, considerations of safety and regulation raise the need for new investigations in certain areas, and for that purpose we are using a variety of animals. In the discussion which immediately follows this portion, Dr. Urbach will have more to say about the extrapolation of information from animals to man, as well as the apparent significance of radiation changes observed in human skin.

MEDICAL CONSIDERATIONS

Frederick Urbach, M.D.

I will now briefly discuss some of the things that have been known for some time about acute and chronic effects of ionizing radiation on skin.

As Dr. Forbes has pointed out, this meeting is dealing with a type of radiation which, by medical standards, is relatively soft; e.g., from 50 keV on down. For a number of reasons, there exists considerable lack of information about the long-term effects of such radiation on the skin.

Certainly, in the very early days of radiology, much of the radiation produced by the old gas-filled tubes was of this quality; but, at that time, methods of measurement were inaccurate and even the exact spectrum emitted by such tubes was uncertain. In more recent years, clinically useful soft radiation has been in the Grenz-ray range, those at the lower limit (20 keV) of what you are interested in. Some 35 years ago, it became apparent that chronic exposure of human skin to radiation could have very damaging sequelae. We have a fair amount of information on effects of ionizing radiation on the skin, based on studies done with radiation somewhat harder than that which you are interested in. That x rays can have an effect on the skin was noted soon after their discovery. By 1896 it was already known that this radiation could have a very striking immediate effect on the skin, and by 1898 it was already known that some very traumatic and long-lasting effects might take place.

It is possible to give a sort of general classification of the kind of changes that ionizing radiation can produce in skin. It is useful to consider first the reversible changes, secondly, conditional reversible changes, and thirdly, irreversible changes.

As Dr. Forbes has already pointed out to you, the most common earliest reversible change is the production of reddening of the skin, erythema. If the dose is appropriate and the quality of radiation is such that most of it is absorbed in the superficial layers, it is possible to produce reddening of the skin which disappears and, as far as one can tell later, nothing more happens.

Another reversible effect is on hair growth, both in animals and in man. It is possible to give a dose of radiation that will stop cell division in epithelial cells so that hair ceases to grow temporarily and falls out. With proper dosage it begins to grow again after a period of time, apparently with no permanent ill effect.

The third system that shows reversible effects are the sebaceous glands (the fat-producing glands in the skin) which can also be affected temporarily to produce less sebum.

Except in the production of erythema, the effect of radiation is due to temporary interference with the division of cells, and this then causes a lack of production of the material that is produced by the appropriate organ; i.e., hair or sebaceous material.

Pigmentation, on the other hand, the production of large amounts of melanin pigment in the skin, has been shown many years ago, to be a not totally reversible change. If one irradiates a relatively large area of skin sufficiently to produce erythema and pigmentation, the pigmentation will eventually fade. However, it can be shown that this area of skin is not normal, because its response to an additional later dose of radiation, whether this be ionizing or nonionizing, is not the same as in untreated skin, so that there is some "memory" of the injury. Incidentally, the same thing happens with ultraviolet radiation. In 1899, Finsen showed that following a fairly severe sunburn the skin returned to normal. However, it is possible to show by vasodilatation experiments that the vessels in the treated site are permanently damaged and will dilate more than those of the surrounding skin.

These, then, are the conditional reversible effects. They appear to be reversible, but the skin is damaged so that when additional damage is produced it does not respond normally.

Finally, the irreversible effects. If enough radiation of the right kind is absorbed in the skin this will result in permanent destruction of either hair or sweat glands, or whole skin, with a resulting scar. The irreversible changes come under the heading of radiation dermatitis, particularly chronic radiation dermatitis, and radiation cancer.

The factors that determine the course of any particular radiation injury are quite well known. The first one of these is the dose; that is, the amount of radiation delivered to a particular volume of tissue and whether this radiation is absorbed and to what extent. This, of course, is a function of the wavelength of the quanta absorbed.

Another problem that is quite germane to your interest is that of field size. With relatively large areas, say, several inches square, one gets with the same dose, a larger effect than if the same dose were delivered to a 5-mm-diameter area.

There are several explanations for this. One is the additional radiation absorbed due to back scatter. The tissue underlying the skin, perhaps bone, may reflect some of the radiation upward. Dr. Forbes showed you the scattering and the deflecting of ionizing radiation. Another is that apparently a larger area of skin has a tougher time healing. If one destroys enough tissue, there is more difficulty in restoring it. The smaller area, biologically, may perhaps be replaced better. There are factors in this that we are not very certain about.

One of the most important factors in determining the eventual outcome of the radiation injury is what might be called the time-intensity factor; that is, the rate or increments with time in which a particular dose is given. Instead of giving a total dose of 2,400 rads to a skin cancer in a single dose (which would cure it but leave quite a hole), one can get the same effect by giving 4,000 rads in doses of 400 rads once a day for a period of, say, 10 days, and the biologic effect will be pretty much similar. These relationships have been quite well worked out. The reason that it takes more radiation is because there is rather significant recovery of the cells between doses, so although the amount of radiation may be larger, the biologic effects are the same. At the same time, the sequelae, the late effects, are much ameliorated.

Thus, whether a skin area gets a single large exposure or many smaller exposures leads to different results. And I think this is of significance to you. It is one thing to get one's hand into the pencil beam of a machine that puts out even 100,000 rads a minute, even if it only irradiates half a square centimeter; it is another thing for an area to receive 100 rads a day for 10 years. The response of the skin will be different.

In addition to this, there are constitutional factors. These factors differ from man to man. Just as in sunburn, people who are light-skinned are more susceptible to sunburn and their skin tends to be more responsive to ionizing radiation.

It may be worthwhile to briefly describe the amounts of radiation required to produce some of these things. With radiation of 100 to 120 kVp and half-value layers in the range of 1 to 2 mm aluminum to an area of 2-inches square, it takes between 500 to 800 roentgens in a single dose to produce erythema. This is a sizable dose. And, as Dr. Forbes pointed out, the erythema usually appears in a day and then disappears and recycles. Eight to 14 days later the area gets quite red and painful. This then subsides, pigment begins to form and, frequently, a month later, on the 35th to 40th day after radiation, another wave of erythema appears which may last 2 to 3 weeks. The exact reason for this dilation and contraction of blood vessels is still unknown today. Presumably, different levels of blood vessels in the skin are affected and behave differently. Of importance is that one of the effects of radiation is significant reduction of large and small blood vessels.

That one can epilate hair was observed in 1897 by an Austrian dermatologist named Freund, who probably was the first one to use x-rays deliberately for therapeutic purposes. Freund read an article in the New York Times (which had reached him some 3 weeks late by boat) which stated that a physicist at Columbia who was working with these new rays had lost his hair. The New York Times made a big joke out of this observation. Freund didn't think it was very funny, he happened to have an infant patient who had a very large hairy nevus, one of these huge malformations of the skin where practically half the body was covered with hair. He proceeded to borrow the only available equipment in Vienna from the Physics Department and irradiated this child deliberately and, indeed, caused the hair to fall out. It is fascinating that this lady was recently rereported; some 60 odd years later she turned up in Israel, at age 70. She has severe radiation dermatitis of the skin, but is still alive and never developed cancer.

Removal of hair by radiation was once practiced extensively. There was a lot of ringworm of the scalp and no other way to treat it. As a matter of fact, the Department of Radiology at the University of Pennsylvania was instrumental in developing a rather elegant technique for removing hair without overlapping the beams so that no permanent epilation occurred at the field edges.

It takes about 350 R or thereabouts of superficial x ray to make hair fall out temporarily, and a single dose of the order of 1200 R causes permanent epilation.

Figure 11 illustrates the radiation changes we have discussed. It shows a patient who has permanent epilation of the hair. It so happens that she was treated because she had a carcinoma on the scalp. In the area of x-ray epilation there is a scar, and the hair is completely gone.

Figure 12 shows some of the late effects. The pigmentation is at the area of x-ray therapy, and there is a small healing ulceration. The pigmentation that develops in this area is very striking and lasts for months or years. The more superficial the radiation is, the less the ulcerating effects but the more striking the pigmentation.

Months or years after significant radiation exposure, there develops atrophy of the skin (fig. 13). The skin becomes thin, and one of the striking features is the development of dilated blood vessels which are called telangiectasis and which may progress with time. It is rather typical of radiation scars that they look cosmetically extremely well early, but, as time goes by, the dilated blood vessels, which are evidence of injury to the deeper vessels, appear and the scar takes on the rather typical appearance of a mild but distinct chronic radiodermatitis.

There have been some studies as to how much radiation the skin can tolerate without these early changes appearing, and it seems that with superficial radiation (80 - 150 keV) something of the order of divided

Figure 11. Permanent x-ray epilation of hair.

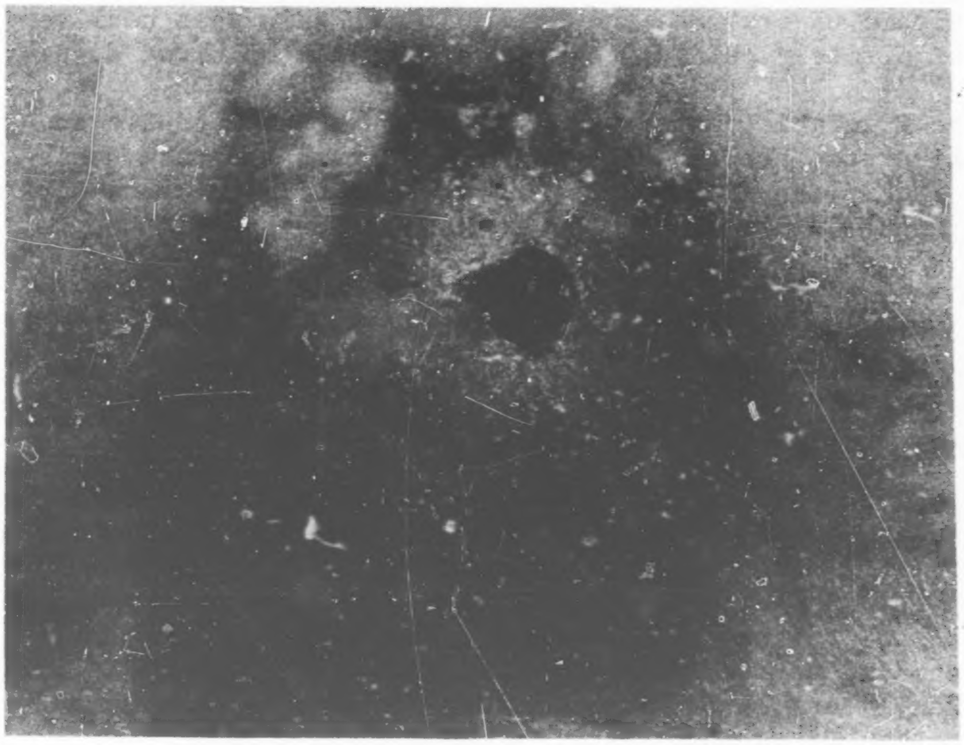

Figure 12. Late effects on scalp as a result of superficial x-ray therapy.

doses up to totals of 1,000 or 1,500 R seem to leave no permanent sequelae. This figure may be low. There is no question, however, that doses upwards of 3,000 to 4,000 R will cause first these superficial atrophies and telangiectasis, and can cause a variety of other problems.

Figure 14 demonstrates the problems of chronic radiation dermatitis - this is the kind of patient we used to see. This individual was a physicist for 30 or 40 years and, early in his career, used x-ray machines of one kind or another. As a matter of fact, he ran a radon mill for a while and received thousands of roentgens in small doses over many years. His hands show dilation of blood vessels and ulceration, an early tumor, disturbances of nail growth, et cetera. These are the late changes of frequently repeated small doses of x ray over long periods of time, the sort of thing that we don't see much of any more simply because the hazard is well known.

It may be worthwhile to show you what happens in the skin in late radiation dermatitis (fig. 15). The upper layers of skin are thin, and the upper part of the dermis, where all the blood vessels and connective tissue are located, is altered. One also can see blue-gray deposits of abnormal elastic tissue. You will notice that this change extends deeply.

Figure 16 shows probably one of the biggest problems one encounters; namely, deep down in the skin the blood vessels are enlarged and there is marked thickening of the wall of these vessels and finally they just close off completely. This seriously interferes with blood flow to the skin and causes chronic ulcerations and cracks in the skin that heal very slowly and are exquisitely painful because of the lack of blood supply.

There is significant evidence that the dose schedules and qualities of radiation that are now used to treat tumors; that is, doses of 4,000 to 5,000 rads given in a few weeks, cause significant radiation scars but that malignant tumors do not appear in such scars. If they do, this phenomenon must be exquisitely rare.

The skin cancers that have been reported and those we have seen have primarily occurred in patients who have received small doses f radiation over a very long period of time to a large total dose. The majority of these early ones were industrial and professional people: physicists, dentists who held x-ray film in the mouth with their fingers, diagnostic radiologists who sat in front of fluoroscopes with a foot on the button and a lead sheet in front but with no protection over toes and hands, et cetera.

Then came the patients who were irradiated for the removal of hair or for acne and received 50 or 100 R of x ray once a week for 5, 6, or 7 years. Many years later many of these people developed skin cancer.

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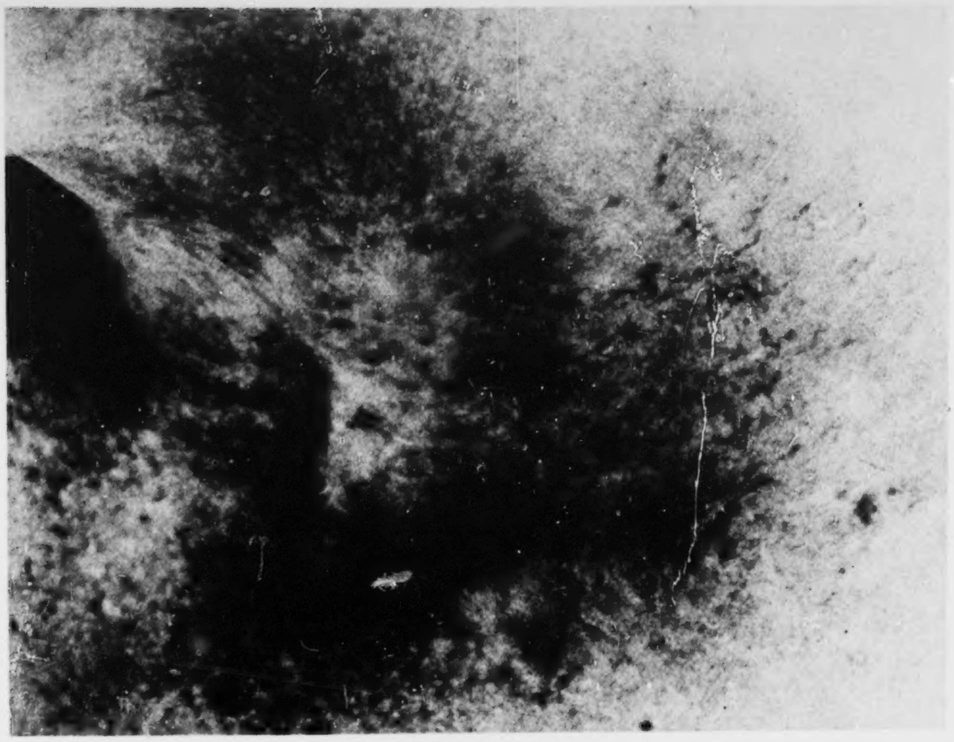

Figure 13. Atrophy of skin as a result of superficial x-ray therapy.

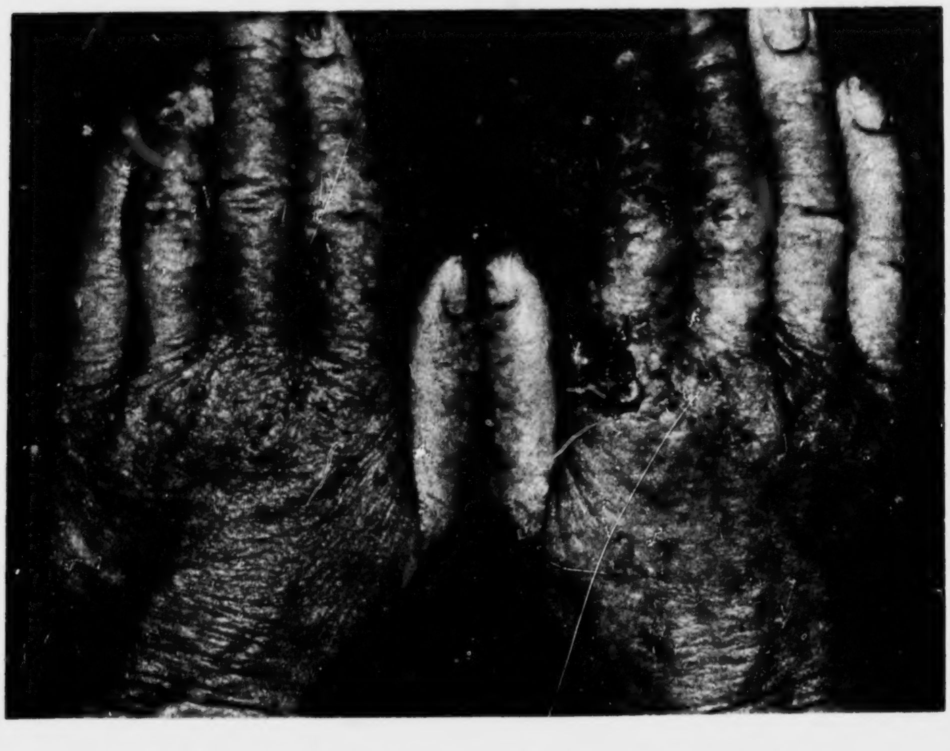

Figure 14. Chronic radiation dermatitis.

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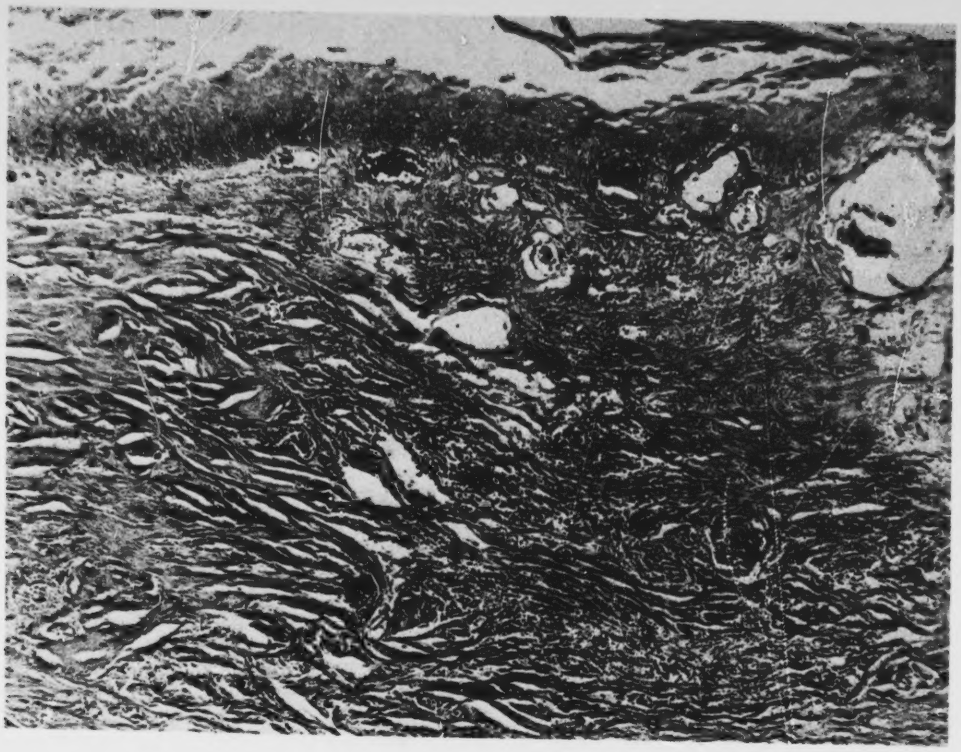

Figure 15. Late radiation dermatitis.

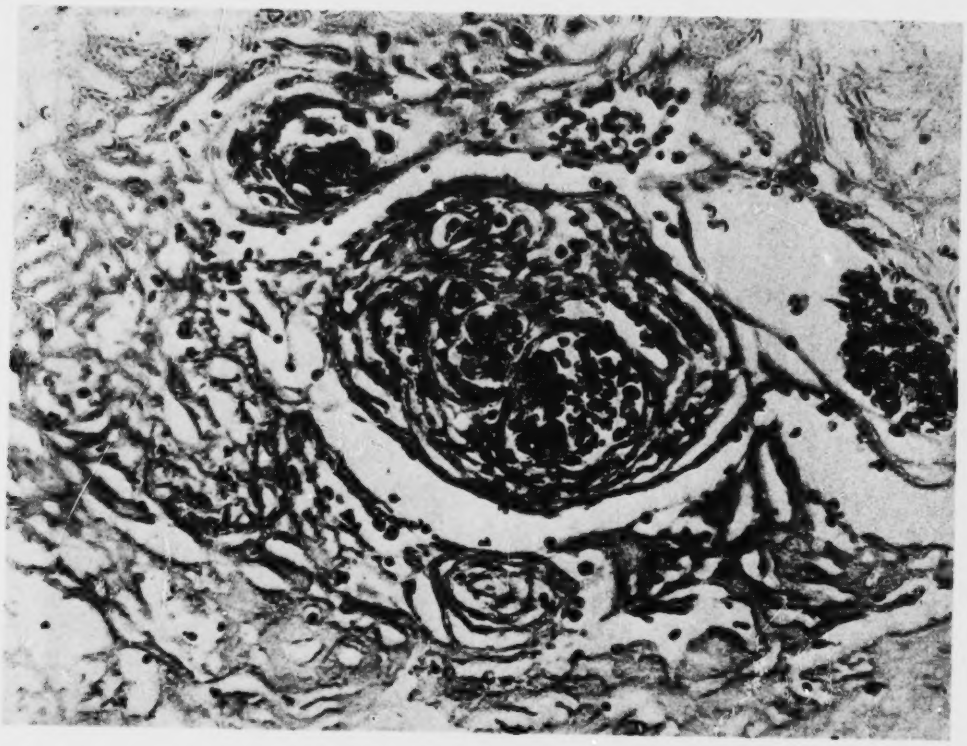

Figure 16. Blood vessel enlargement and wall thickening in late radiation dermatitis.

One observation which is of practical importance to all of you, if you should have an unfortunate accident with the type of radiation you are working with is this: there is overwhelming evidence that x-ray induced skin cancer does not occur unless there is a significant and visible radiodermatitis that has been present for some time. In other words, one can't have a single area of damage that completely heals over and then 20 years later develop skin cancer in that site when the changes which I showed you (telangiectasia, atrophy, pigmentation, etc.) are absent 5 years or more later. The median time between x-ray exposure and cancer production is of the order of 10 to 15 years.

We don't know a great deal about what happens with softer radiation. There are a few cases on record of patients treated with Grenz ray developing skin cancer. Grenz-ray radiation lies in the range from somewhere between 10 and 20 keV, with half-value layers of the order of 15 to 50 microns of aluminum.

This type of radiation requires more energy to produce erythema of the skin, and certainly doses up to 4,000 to 5,000 rads have been given to the skin without any permanent ill effects. In those cases where radiodermatitis has appeared that have been carefully investigated, the radiation was almost always administered with multipurpose machines, or in other words, beryllium window machines that could be used at 100 keV or 10 keV. If the switch was not in the right position, it was possible to give an awful lot of radiation in a short time and think it was Grenz ray when, in reality, the machine produced an awful lot of high-energy x rays.

We have had occasion to see one patient who had an accident with an x-ray diffraction unit. This was an engineer from one of the very famous European concerns who actually designed some of this equipment and came to this country to demonstrate it. Something was wrong with the collimation of the beam, and, although he knew all about it, he apparently connected or disconnected all the safety features he had built into the machine and adjusted the direction of the beam with a screwdriver, holding the heel of his hand in the primary beam for something like 30 minutes, about 4 or 5 centimeters from the exit port. Although we never had the data for accurate calculation of dose, it is safe to say that it was of the order of hundreds of thousands of rads at about 30 keV. Four or five hours later he had a huge painful blister and erythema in the radiated site (fig. 17). Histologically, it looked like all the epidermis had been destroyed (fig. 18). Two years later, the patient came back to the United States and we had the opportunity to see him again (fig. 19). You will notice that his skin had remarkably recovered. The only thing that one could see were little areas of telangiectasia scattered here and there. Histologically, he really had relatively little damage. He had a few changes in the upper connective tissue but strikingly little for the amount of this very soft energy he had received.

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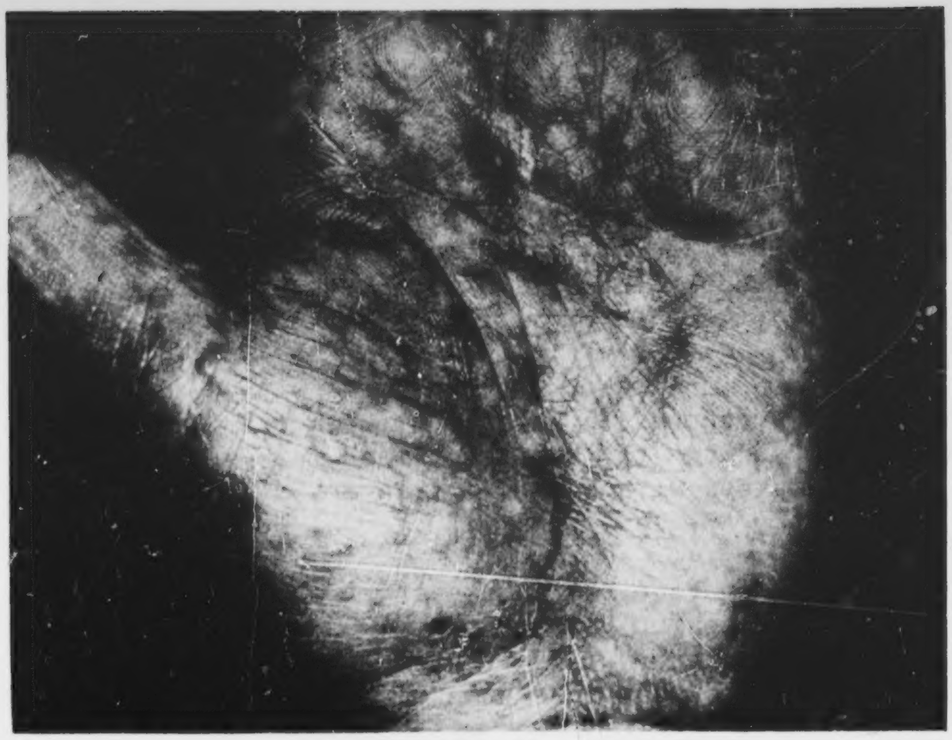

Figure 17. Blister development several hours after exposure to primary beam of x-ray diffraction machine.

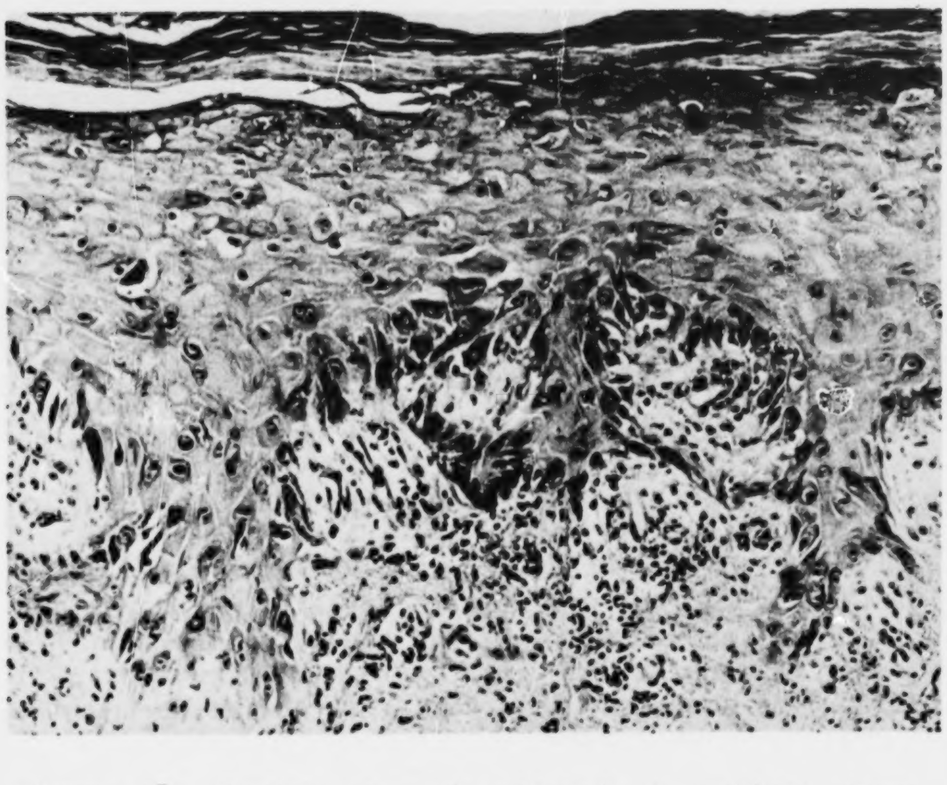

Figure 18. Destruction of epidermis in patient shown in figure 17.

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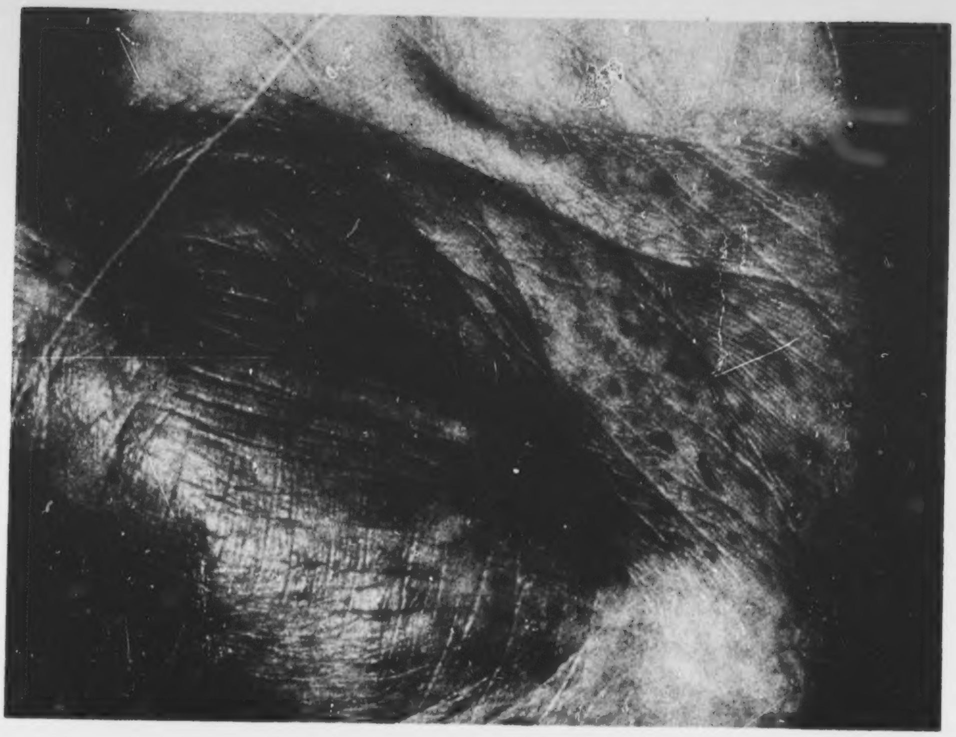

Figure 19. Skin recovery of patient shown in figures 17 and 18, 2 years after exposure.

As far as the skin is concerned, two types of problems arise. One kind are the acute accidents where a few hours later a blister will form. But, in general, it appears that these injuries do heal, unless the radiation was right over a bone and destroyed the bone underneath. Apparently, the permanent skin damage is not too great, at least in the patients that we know of. Conservative, expectant treatment seems to be the best choice in such circumstances.

What concerns us most, and about which we really have virtually no information, are long-term effects of small doses of radiation on people who will be working with such equipment for a very long period of time. All we can say safely is that systemic effects do not occur, since this radiation does not penetrate much beyond the skin.

One group of investigators irradiated mice with whole body doses of 50 rads a day with a Grenz-ray machine, to a total of 30,000 rads over an 18-month period. None of these animals showed any system toxicity. The LD_{50} for mice with conventional equipment is about 600 rads. At the end of one year (20,000 rads) the animals showed absolutely no damage, except just a little fuzziness of the hair. The animals who received

30,000 rads (which is 50 rads a day for a year and a half) developed a few squamous carcinomas of the skin. Remember that treatment consisted of divided doses of Grenz ray over very long periods of time, in an animal where virtually all this radiation is absorbed in the epidermis and where cancer is very easily produced, as compared to man. Certainly, it would appear that such radiation is not systemically harmful. Thus it appears that blood counts aren't very helpful when one works with this type of equipment. And I am not at all sure that looking at the skin will tell as much before 20 years have elapsed.

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DISCUSSION

DR. CHAMBERLAIN: I have seen quite a few of these. One was, I think, at least 13 or 14 years ago, a university research student who got similar blisters on his thumb and finger, and again we decided to watch and wait. He received probably of the order of 30,000 to 40,000 rads at the surface, but it was very soft radiation. I have seen him again as recently as a year ago. His fingers are a little glossy with a little atrophic change on the surface, but they were not amputated, and I think this is the right thing to do. I think a good many people have amputated rather prematurely and unnecessarily for injuries by these very soft wavelengths of radiation.

There is one other test that you didn't mention and that is sometimes of help if the exposed area and dose are sufficient. This test, chromosome aberration studies, has been perfected in recent years. It is another method which is remarkably sensitive. The chromosome aberrations are not necessarily harmful. They are an alteration, but they should not be equated with somatic damage. This test is now the most sensitive biologic indicator of radiation change that is available.

Recently, we had a case of a man operating an electronic welding apparatus, whose film badge showed very high readings. He wore it on the front of his shirt, and the readings were so high that it seemed impossible for him to have received this dose. His skin showed no changes, there was no depilation of the hair, and there was no erythema. I followed him over many weeks. One was left with the problem as to whether his film badge had been inadvertently irradiated in the place where it was stored, whether he had irradiated it purposely somewhere else without irradiating himself in order to get attention and perhaps compensation, or whether somebody else had maliciously irradiated his badge.

It was very important to figure out whether this man had in fact received something over 1,000 rads of penetrating radiation. In this case, we were able to get chromosome aberration studies done and say unequivocably that over any reasonable area of his body he could not have received such a dose of penetrating radiation. It was of important negative value, because he did not show the chromosome changes.

DR. RUDMAN (ADELPHI UNIVERSITY): In relation to the film badge, I was told once that a person had taken his badge home and had accidently left it on the television set and that he had caused the company all sorts of difficulties trying to trace the radiation. It would be a good policy to keep film badges stored at the company and not to let them out of the company or out of any working area and keep track of exactly what is done with them.

DR. CHAMBERLAIN: As a matter of fact, it is very difficult to get any significant radiation exposure to a film badge out of a television set, in spite of the reports in the newspapers.

DR. RUDMAN: The other point that I would like to make is that about 5 years ago I read in the popular press that a so-called wonder drug had been recently discovered which could treat some of the irradiation damage to the skin. I was wondering if this is true and if there is any such drug available or not.

DR. URBACH: Dr. Chamberlain and I both nod to each other and think about "cactus juice", aloe vera. There was a flurry of activity some ten years ago about this, but I am afraid that, first of all, it has been recommended for all sorts of things and has been around for at least 50 years. We tried it on chronic radiation ulcers and never found that it had any significant effect.

DR. CHAMBERLAIN: I think that I should say something about this, if it is the one. A book came out about 2 or 3 years ago called "Green Medicine". It is a book about various herbs. In it, the University of Pennsylvania was quoted as having recommended aloe vera. Actually there was a letter from one man from Penn saying that he was trying it in some experiments, and somehow this letter was transferred to the company. But I can assure you that there is no scientific basis that I have been able to find that this or anything else works for radiodermatitis. Usually my feeling is the least you do the better.

DR. URBACH: That's right.

DR. CHAMBERLAIN: Ordinary emollients prove best.

DR. URBACH: Cold compresses or soaks are useful during the acute phase. I think the most important thing is, as Dr. Chamberlain has pointed out, to be conservative. To take off fingers for this kind of radiation, unless there is clear destruction of bone and severe chronic pain, which would be very unlikely, would be premature. It is best to wait. These things can be treated years later, if necessary. In our experience with this type of injury, conservative therapy, is the treatment of choice. As has been pointed out, many of the injuries occur on the fingers, where the horny layer is very thick and a great deal of this radiation is absorbed by dead tissue. So, the dose that gets down to the living tissue is probably a lot less than the dose which is incident at the surface, because of the relatively soft radiation.

DR. CHAMBERLAIN: I would like to make one other comment. I think there are two things that we need that the conference might discuss somewhat tomorrow afternoon. One is that it would be well if there could be a mechanism to collect the cases of accidents. We ought to have some idea of what has happened to the people who have had large exposures, if possible. I do not know of any repository or any group that is collecting these particular types of problems. They can be illuminated somewhat by errors or accidents that have happened in the course of medical therapy, particularly by people who have used beryllium window tubes. The common trouble with berryllium window therapy tubes is not the alteration of voltage, it is the leaving out of the filter. If you leave out the filter in these very soft radiation sources, you can jump from the expected 100R per minute to something like 200,000R per minute. This has happened a few times.

The second is that I think it would be helpful to have some kind of a list developed by someone, and maybe I am suggesting this to the Public Health Service, of physicians who have had at least some familiarity and some reasonable experience with situations like this. At least this could be helpful.

VOICE: Wasn't there, about a year or so ago, publicity given to use of FUDR or BUDR?

DR. URBACH: That I don't know. 5-fluorouracil has been used extensively for the removal of actinic, that is ultraviolet-induced pre-malignant lesions, but it destroys them; it doesn't promote healing.

DR. CHAMBERLAIN: He may have read stories of this being used for skin cancer.

DR. URBACH: For skin cancer, yes, but incidentally, it does not work very well on radiodermatitis and I would recommend against it if I were the attending physician. I have personally treated several people with chronic radiodermatitis recently. If you want to scare yourself out of 6 years worth of growth, put it on that skin. All the skin eventually heals up, but first all the skin almost falls apart and it really scares the living daylights out of one. The first time I used it, I spent several weeks worrying about what was going to happen to this poor patient. I don't recommend it for use on severely radiation-damaged skin.

DR. CHAMBERLAIN: I don't think we can go into all our medical problems. As a matter of fact, even radon ointment was used very effectively in the old days. Many of us have treated radiation-induced cancer with more radiation, too. It is possible, but let's not get you confused with it.

DR. URBACH; I don't know any therapy other than time and, if necessary at a later stage, the removal of the affected area. But it is my opinion that in most cases with superficial radiation, the most conservative therapy, doing as little as possible for as long as possible, is certainly indicated.

PUBLIC HEALTH EXPERIENCE IN X-RAY DIFFRACTION

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Before discussing the subject of public health experience, it might be well to consider certain changing attitudes in matters of health protection, particularly in the field of radiation. It has only been within the last 10 or 15 years that radiation exposure, except in the case of fall-out from nuclear weapons testing, has been really considered a public health problem. Before that, it fell more into the category of occupational health and only the operators of radiation equipment and users of radioactive materials were of concern. With the rapid expansion of atomic energy and the many uses of x rays, it became apparent that radiation has now truly become a public health problem. This attitude is enhanced by the fact that genetic considerations are the controlling factors in limiting exposures.

There are many risks to which our citizens are now subjected, in the nature of environmental disturbances that could have an adverse health effect. Even when risks are encountered during a worker's occupation, they are becoming to be considered more and more as another aspect of the overall environmental contamination problem.

During the early 20s and 30s, there were occasional reports of injuries to x-ray diffraction workers. These generally consisted of x-ray burns either of the fingers or of parts of the head that were inadvertently placed in line with a pencil beam of x rays used in a diffraction device. Another cause of overexposure is exemplified by the story of a laboratory worker who attempted to locate a small steel splinter imbedded in his finger by using an x-ray diffraction machine and a fluorescent screen. The result was serious damage to his finger resulting in an amputation.

The great stimulation of industrial activity resulting from World War II, and also the need for quality control procedures to meet rigid government specifications resulted in a vast increase in the use of x-ray diffraction and spectroscopy in industry and in research. It also resulted in the entry into this relatively new field by workers with minimal training. Increased reports of accidental overexposures resulted in two reactions. Insurance companies specializing in workmen's compensation began inspecting industrial x-ray equipment, including diffraction devices, for their own protection in attempting to reduce compensation claims. The Division of Labor Standards of the U.S. Department of Labor held discussions of the problem with representatives of the National Bureau of Standards. This resulted in the establishment of a committee to draft a safety code for the industrial use of x rays under the sponsorship of the American Standards Association. After several years of work, American War Standard Z54.1 was issued on April 15, 1946. It contained a brief section of about a half page listing a few recommendations for x-ray diffraction units. These recommendations have served as the only recognized set of national standards for this work for almost a quarter century. Some of the basic recommendations for all industrial x-ray equipment, first appearing in the same standard, were revised in 1964 by the publication of NBS Handbook 93. The need for better standards is evident from the bad experience with such equipment.

Some time ago I was given a copy of an unpublished report by an insurance company describing eight separate overexposure incidents in different plants, in a single year (1953), all resulting from the misuse of x-ray diffraction equipment. In each case, workers had used x-ray diffraction equipment for fluoroscoping small machine parts or ceramic insulators by holding them with their fingers or with a pair of pliers in an x-ray beam and viewing the shadow on a fluoroscopic screen. The fact that the writers of this report preferred that the details not be published, indicates that there are probably many such incidents which have occurred over the years that have not been reported for one reason or another. I have heard several stories of efforts to avoid publicity or to "cover up" accounts of x-ray overexposures.

Reports of comprehensive studies of radiation accidents involving x-ray diffraction equipment that have come to our attention have shown shockingly high numbers of accidents, much higher than for any other radiation equipment use that we know of today.

In 1968 Lubenau et. al. (1) reported that in Pennsylvania, over a period of about 11 years, there had been 17 accidents involving 22 individuals exposed to excessive x radiation from analytical x-ray sources. They reported blisters, reddening of the skin or pain as the first indication of injury. In some cases, film badges indicated overexposures.

Four of the 22 exposed persons underwent amputation of exposed fingers with possible long term effects. Lubenau's group reported that carelessness, inadequate instructions and equipment failure were some causes of accidents, with defective shutters a common failure.

Also in 1968, Lindell (2) after a lengthy international investigation of occupational hazards in x-ray analytical work reported that in 5 countries; Canada, Denmark, Finland, Norway, Sweden and U.S.A., representing 800 x-ray units used for analytical work, 53 of them had been involved in accidental overexposures and that 26 of these resulted in clinical symptoms such as, visible erythemas to eyelids, faces and fingers. An additional ten cases involving necrosis to fingers were considered to constitute severe injury. When we consider that there has been an accidental radiation exposure in one of every 15 units in use, as shown by a substantial sample, it appears to indicate serious lack of control over this source of radiation injury. Lindell estimates the accident rate as about one per year per 100 units in use. When we examine the details of many accidents we see that a common cause of overexposure has been the simple fact that an operator has placed his hand or head in the x-ray beam without knowing that the machine was in operation or that a protective shutter was open, or not operating properly. One case that occurred recently, resulted from the fact that a worker nearing the end of a long exposure of several hours, turned off the equipment at the end of the work day, considering the exposure to be adequate. On the next day, another worker set up an experiment not knowing that when he turned on the main switch, the shutter was open, and the timer "on" with unexpired time left on it. This activated the beam without his knowledge. Here again, there is clear indication that when the intense x-ray beam (hundreds to thousands of roentgens per minute) used in this type of work is on, there should be a clear signal that the operator should take precautions to avoid exposure.

During a recent visit to a large industrial research laboratory in which there were about 35 x-ray diffraction machines in different departments, it was my observation that not a single installation met all of the recommendations of the old war standards nor many of the generally accepted radiation protection standards now considered to be good practice.

It is my personal opinion, after reviewing the circumstances of many incidents of radiation overexposure, that one reason for poor safety practices is the misuse of warning signs and signals. In many cases it is the overuse of warnings that causes workers to disregard legitimate and important warning signs. I have observed many areas placarded with signs designating "Radiation Area" in a place that could not be reasonably considered a radiation area as usually defined. Most research and industrial laboratories use radioactive materials and thereby are subject to AEC regulations, and besides many states now use the AEC standards as part of state regulations. There should certainly be a clear understanding of what a Radiation Area, as specified by Atomic Energy Commission Regulations is. No x-ray diffraction room that I know of could be a radiation area. Perhaps a new term is needed. Practically, most AEC radiation regulations should apply to all uses of radiation in the interests of national uniformity, yet it has been our experience that there are perhaps as many Radiation Area signs used where there is no radiation area, according to the definition, as there are signs legitimately posted. It is not unusual to find radiation warning signs in places where radiation no longer exists. It is also not uncommon to see red warning lights without any indication of their meaning. Sometimes it may mean, "Danger, keep away" whereas it may merely designate a fire exit. It is our belief that a regular review of all warning signs, labels and signals should be conducted to make sure that they are meaningful and understandable. In this way, workers can be trained to pay appropriate respect to these important means of protecting them.

After a review of many accident reports, it seems obvious that a few basic safety measures or devices could have prevented most of the accidents. National Bureau of Standards Handbook 93, which is intended to provide general recommendations for all non-medical x-ray sources, including x-ray analytical devices, states that "open installations" are to be used only when necessary to satisfy operational requirements (Section 2.3). It was published over six years ago, yet most x-ray analysis devices that I have seen have not been enclosed,as provided for in the recommendations, and there appears to be no operational requirement that they be open installations. X-ray equipment enclosures should be equipped with safety interlock switches and, of course, be adequately shielded. If necessary, there should be meaningful warning signs posted.

In addition, for the protection of the operator, there should be a clear indication that the x-ray beam is turned on and also that the shutter is open. My preference is for illuminated warning signs that are illuminated only when the warning should be given. Some machines do offer this protection.

Whenever the x-ray beam, after passing through a camera or a sample, is still sufficiently intense to constitute a radiation hazard, there should be a shield or beam stopper to attenuate it before it reaches a point where it might expose someone. It has often been found that an unnoticed hazard has been created by the removal of a beam stopper.

There should not be too much reliance placed on the effectiveness of film badges or other personal monitoring. Because of the small size of the x-ray beam used for this purpose, there is little likelihood that the beam, which is the greatest danger, will expose a small personnel monitoring device. Surveys of many installations indicate that the scattered radiation at the point of closest approach by an operator's body, except for extremities, is usually not over a few milliroentgens an hour. It may be that personnel monitoring constitutes a false sense of security and should not be used.

When the new N43.1 Committee of the American National Standards Institute (formerly the USASI and before that the ASA) started to develop new standards to replace the 23 year old ASA War Standard (Z54.1), it became "hung up" on such terms as "fail-safe interlocks" and "reliable" which are very important terms in this field. The result was the designation of a new committee (N43.6) to draft a standard for "Reliability and Fail-Safe Aspects of Control Circuits and Devices."

Public health experience shows clearly the need for improved, practical, clearly stated standards of radiation protection for x-ray analytical equipment and its use.

The standards should meet the needs of designers, manufacturers and users of such equipment and also those of us who must see that safety standards are followed. In other words the safety standards should not increase the cost of installations unreasonably, they should not interfere unduly with their use, and they should be enforceable.

References:

(1) Lubenau, J.O., Davis, J.S., McDonald, D.J. and Gerusky, T.M., "Analytical X-ray Hazards: A Continuing Problem", Health Physics, June 1969.

(2) Lindell, B., "Occupational Hazards in X-ray Analytical Work", Health Physics, December 1968.

DISCUSSION

DR. SAMSON: Regarding the personnel monitoring that was just indicated, I feel that the film badge still, despite the fact that we are using a small beam, is extremely useful. If diffraction apparatus is working properly the film badge doesn't monitor much, but it indicates when something is not designed properly, because then you get too much secondary scattered radiation, and so on. For that reason, I feel that the personnel monitoring still has its place.

For example, let's say a faulty design of a beam trap or something of this sort may give rise to quite a bit of fluorescence or secondary scattering, but, in the long term, gives quite a bit of exposure.

PROFESSOR BLATZ: My reaction to that would be that it is my feeling, and I think it is in many standards, that every time a setup is changed, it should be surveyed with an instrument, and a survey would be a more reliable way of finding out if anything is wrong. I still feel that that little patch of film on somebody's lapel or belt is a poor way of discovering if something is wrong, also considering the fact that most serious accidents have involved the beam itself rather than scattering.

DR. CHAMBERLAIN: I think maybe the hangup here is on the term "false security," because actually this is true for film badge methods of monitoring or direct reading chambers, or many situations. And many of us believe that the real purpose of these is a general sense of how the total program of radiation safety is going. Almost never do they truly give you a precise indication of what hazards a person may or may not have gotten into. They only tell you where the badge was.

People can put their foot or their hand or their face into all kinds of areas that are not monitored unless you do something special about it.

I quite agree with Professor Blatz. When I first started out in the radiation world, I regularly saw dentists and doctors and medical patients who had visible somatic troubles engendered from radiation. These are now getting rare, but it doesn't mean that we still don't have lots of things we can do to clean up and make better the medical and dental situations. But we don't see gross somatic injury to human beings now, or at least very rarely in medical or dental situations, Although design often can make it much easier to not get into trouble, I personally think that on top of that, the other major thing we ought to work for is some reasonably appropriate degree of education of the people who are using it. The combination can usually result in pretty good safety.

DR. SAMSON: There does not exist any interlock that is 100 percent foolproof, and we all know that.

PROFESSOR BLATZ: That is the purpose of this new committee.

DR. SAMSON: And, therefore, one may ask oneself, if the personnel supervision is not the most effective thing in the first place. An interlock that can malfunction is really more dangerous than no interlock at all. If you trust an interlock and depend upon it and it malfunctions, then it really gives you a false sense of safety; whereas -- and this is my personal opinion -- if the user is properly instructed and he knows where to look and what to look for, it is also safety. Safety interlocks are necessary. But one of the most important things, I think, is proper supervision and instruction to the users.

PROFESSOR BLATZ: I think there is a need for both of them.

You mentioned the safety interlock switches, which points up the fact that switches that we are using today are the most unsafe design that you can think of. When the spring breaks, it breaks in the closed position. We could learn a few things from the railway signal people. On switching devices, if something goes wrong, a light lights up. If an interlock fails, a light should light up. Also, if the light bulb burns out, it trips the relay so that everything stops. So, you could make it foolproof, and these things aren't terribly expensive.

I still think, however, that supervision and instruction shouldn't be overlooked. I don't propose for a minute that you provide as near a foolproof device as you can and then let anybody operate it without instructions. I think there is a need for both.

but we are still seeing them, and I see several a year from industrial occurrences. Some of the most traumatic ones are from these diffraction and spectrographic units. They are tricky and they are also very frequently used by people who don't properly appreciate the total picture of monitoring, safety, and common sense.

PROFESSOR BLATZ: It is my feeling that these devices can be made virtually foolproof. I mean, even to the extent that if you put your hand in the beam when it is in operation, the capacitance could shut the machine off, if you wanted to take that trouble. I think if you did that, you could eliminate all of the accidents.

DR. CHAMBERLAIN: Are there other questions or comments?

MR. ROLAND JALBERT (Los Alamos): In talking about enclosed units, were you thinking about installing interlocks where none existed or adding a cubicle or a box over the head of the diffraction unit to make it enclosed instead of open?

PROFESSOR BLATZ: It is my understanding, and I support this, that every x-ray diffraction machine should be in a separate cubicle into which only the operator is admitted, and this, as I understand it, is the way it was written up in Handbook No. 93, but nobody follows it. This should be interlocked. I have seen x-ray machines in large laboratories operating, with no indication, no sign, and people cleaning in the same room. They know enough not to go near any equipment, but you can't depend on it.

MR. JALBERT: One could interlock all the ports in such a way that no beam could get to the outside unless there was a camera or some other unit to receive the beam, so that no one could expose himself without violating an interlock, and then being an enclosed unit, without adding a cubicle.

PROFESSOR BLATZ: It could be a cabinet-type unit, which is also provided for, whether it is a cabinet which just encloses the machine or a cubicle that encloses the machine and the operator is the choice. But, if you substitute other equivalent means, I suppose it would be satisfactory. But that is not the way the standard is written.

DR. CHAMBERLAIN: This, again, is a common problem. It is possible to make anything truly idiot proof, if you go to enough trouble and if you put enough things in it. Of course, you finally get to the point where you have to have safety factors on the safety factors, and I suppose there is some point of ridiculousness.

SESSION B

ANALYTICAL X-RAY EQUIPMENT AND ITS USE

Moderator: Reuben Rudman, Ph.D.
Adelphi University

SURVEY OF X-RAY DIFFRACTION AND X-RAY SPECTROSCOPY EQUIPMENT
Reuben Rudman, Ph.D.

SAFETY DEVICES FOR X-RAY DIFFRACTION
Sten Samson, Ph.D.

RADIATION SAFETY AND X-RAY DIFFRACTION TECHNIQUES
R. A. Young, Ph.D.

SURVEY OF X-RAY DIFFRACTION AND X-RAY SPECTROSCOPY EQUIPMENT

Reuben Rudman, Ph.D.

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There are a number of comprehensive reviews of x-ray instrumentation already in print (see References). However, inasmuch as the present conference has brought together a number of individuals not necessarily acquainted with the general principles of commonly encountered equipment, some fundamental principles will be reviewed briefly.

Modern x-ray instruments are used for many purposes and come in various shapes and sizes. However, aside from those using radioactive isotopes as x-ray sources, they are all basically the same. A number of the applications have been discussed in a previous paper. The present discussion is limited to instruments operating below 100 kv and used for diffraction or spectroscopic studies.

The emphasis will be on possible sources of x-ray leakage -- either through instrumental deficiencies (e.g., faulty design or construction; improper interfacing by the user, or through operator deficiencies, e.g. inadequate training; carelessness; conscious bypassing of safety interlocks).

The typical instrument includes three basic systems: x-ray source, specimen support and/or holder, and detector. In any given experimental setup, these three systems may be enclosed in one integral, commercially available unit or they may be three distinct systems assembled by the user. In the latter case, the interfacing of these units is especially critical. Any, or all, of the three systems may be commercial instruments or they may have been designed and constructed under the user's supervision.

At the risk of generalizing, it might be stated that x-ray spectroscopy is usually accomplished with commercial units purchased from one vendor and designed for use by the technical, rather than scientific, staff. X-ray diffraction instrumentation, on the other hand, is commonly found to be assembled from components manufactured by different vendors and interfaced by the user. This is especially true of camera equipment and of older equipment. A number of manufacturers have recently (within the last five years) marketed special shutter assemblies that include various fail-safe features. However, there are still very many older x-ray units in operation and these must be checked very carefully. Special attention must also be given to non-commercial instruments. These are generally designed by senior scientific personnel who are aware of radiation safety precautions. However, because of the special nature of these instruments the interfacing between source and instrument must be carefully monitored.

X-ray beams are extremely small (0.01 cm^2 cross-section) and errors in their detection can arise if a large cross-sectional safety meter is used. For example, a strong reflection encountered in single-crystal diffractometry can give counting rates approaching 200,000 counts per second in a beam approximately 0.01 cm^2 in area. The estimated dose rate is approximately 80 rem/hr. Such a beam, directed at a point in the eye, could exceed in 5 minutes the maximum permissible dose for a year, yet it would give a reading of only 13 mR/hr with a 60 cm^2 ionization chamber. This example and techniques used to detect these effects are found in the forthcoming report of USASI Subcommittee N43.1.

In general, all x-ray sources are similar, while the specimen holder, chamber or orientor depends on the specific application and type of detector in use.

X-rays are generated when the electrons in an atom undergo a transition from a higher to a lower energy level. The excess energy (Δ E) is given off as an x-ray photon. The greater Δ E, the higher the energy of the photon and the shorter the wavelength, λ. The basic point is that there must be an empty low-energy electron level available. How the inner-shell electron is removed is not a primary concern. However, once it is removed any of the higher energy electrons can fall into it; which one does fall is purely a statistical matter. Thus, once a target is affected in such a way that the inner-shell electrons are removed, a characteristic spectrum is obtained as the various other electrons undergo transitions from higher to lower energy levels.

The x-ray photons emitted from the target interact with the sample, and under certain conditions constructive interference of the diffracted waves is obtained. This results in the observed diffraction pattern. The formula describing this is called Bragg's Law: $n \lambda = 2d \sin \theta$, where θ is the experimentally observed diffraction angle; λ is the wavelength; and d is the interplanar spacing of the crystallographic planes responsible for the diffraction of the x rays at that angle. If either λ or d is known, the other can be calculated. In x-ray diffraction, the characteristic spectrum, consisting of a number of lines, must be monochromatized so that only a single λ is used to give the observed x-ray pattern. Under these conditions, unique d-values can be determined. The magnitude of these interplanar spacings furnish information regarding the unit cell dimensions, while their intensities are used to determine the atomic positional coordinates and thermal motions. Some techniques are used for identification purposes only, while others are used for complete crystal-structure analyses of varying degrees of accuracy and precision.

In x-ray spectroscopy, the purpose is to identify the elements present in the sample. As a result, all λ's generated by the sample are measured. In the common spectroscopic system, the high energy source used to generate x rays from a sample is another x-ray beam of sufficient energy to generate x rays from all elements under investigation. Reference to tables of characteristic emission spectra and use of the formula, $\lambda = 12.4/kv$, will serve to indicate the voltage required to generate the necessary primary beam. The x rays emanating from the sample are diffracted by a crystal (analyzer) of known d-spacing. Thus, in x-ray spectroscopy, d is known and λ is calculated from the observed θ.

However, the use of an analyzer crystal is not necessary if the λ's generated by the sample could be determined some other way. Newly developed detectors and multichannel pulse-height discriminators have recently been used to analyze directly all radiation emanating from a sample, on the basis of their energies alone. Such instrument have only recently become commercially available. They can use a radioactive isotope to cause the sample under investigation to fluoresce and thus can be made compact and portable. The radiation safety problems encountered with these instruments are similar to those encountered with the more common fluorescence units, providing the presence of radioactive isotopes is taken into account.

We will now discuss some of the details of construction of the various instruments.

The following equipment was discussed:

1. X-ray tube and generator.
2. Powder camera, Debye-Scherrer type.
3. Powder camera, flat cassette type.
4. Powder diffractometer.
5. Single crystal camera, precession.
6. Single crystal camera, Weissenberg.
7. Single crystal diffractometer, manual and automatic.
8. Spectrometer, manual and automatic.

For details of operation, the reader is referred to:

1. R. Jenkins and J. L. DeVries, Practical X-ray Spectrometry, Springer-Verlag, New York, 1967.
2. E. Kaeble, Handbook of X-rays, McGraw-Hill, New York, 1967.
3. R. Rudman, X-ray Diffraction Analysis, J. Chem. Educ., series in Chemical Instrumentation column, January-June, 1967 (also available as separate reprint from Journal Chemical Education, 20th and Northampton Sts., Easton, Pa., 18042).
4. S. Weissmann, Recent Advances in X-ray Diffraction Topography, pp. 141-191, ASTM Sp. Tech. Pub. #430, Am. Soc. Testing Mat., 1968.)

DISCUSSION

MR. WARREN INGLES (Frankford Arsenal): Would Dr. Rudman consider all these systems safe for his students?

DR. RUDMAN: It depends on who my student is.

MR. INGLES: Assuming you have qualified them.

DR. RUDMAN: If I have qualified them, yes, I would consider them safe. But you do have people that are careless at any level?

DR. SAMSON: You showed in one of your slides a fluorescent screen with a lead glass behind it. I have personally experienced the case where someone lost this lead glass plug and replaced it with a lucite plug, which, of course, is dangerous in an x-ray diffraction unit. So, once in a while take a survey meter in front of that plug and really make sure that that lead glass plug is in there.

MR. INGLES: I suppose there are times when the x-ray beam, instead of being diffracted from the sample holder, could pass all the way through the sample.

DR. RUDMAN: This is the purpose of the beam stop. Dr. Samson, in the next talk, will describe systems for containing the direct beam and the use of safety interlocks.

SAFETY DEVICES FOR X-RAY DIFFRACTION

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INTRODUCTION

Examples of some important factors determining the technique to be used in X-ray diffraction studies are:

(1) State of substance: gaseous, liquid, amorphous, crystalline.
(2) Kind of specimen: bulk sample, powder, fiber, thin film deposit, virus, tissue, small single crystal (of the order of a few microns), medium-size single crystal (~ 0.05 to ~ 1 mm), large single crystal (e.g., solid-state devices), etc.
(3) Kind of study: crystal structure of ordered atomic arrangements, order-disorder, transformation, phase analysis, solid solubility, inclusion, orientation, grain size, texture, dislocation, deformation, Guinier-Preston zones, etc.
(4) Nature of substance: small and medium size molecular structures and inorganic compounds, some of which are damaged slowly by X rays; large molecules of biological interest, often damaged by X rays quite rapidly (~ 24 to ~ 70 hrs); highly symmetrical, complex, intermetallic compounds giving very weak reflections that require special emphasis on good signal-to-noise ratio (monochromator); extremely large unit cells (~ 300 to > 1000 Å) requiring microfocus and small-angle diffraction techniques, etc.

The variety of X-ray equipment used in the study of the structure of matter is so great that the description given here must be confined to those techniques that are most common. Today, almost all chemical laboratories, as well as many physics laboratories, are equipped with single-crystal and powder-diffraction apparatus, and emphasis should be placed on these. In many instances, the same general principles apply, with minor modifications, to a large variety of techniques.

Leak-Proof Joints. If two flat surfaces are brought together, the tiny gap that exists between these is often sufficient to let through a measurable amount of X rays. Therefore, a labyrinth is often used, since it eliminates any straight path to the outside from the area or volume to be sealed.

Four examples of typical labyrinth seals are shown in Fig. 1 (encircled), which represents the cross-section of a chamber designed to accommodate an X-ray monochromator. The labyrinth is of special importance when the adjoining parts are to be moved relative to each other while the X rays are on, as is done, for example, when adjusting a monochromator, an X-ray camera, or a diffractometer.

A properly designed labyrinth constitutes an almost permanently safe seal in contrast to the flat, flange-like joint and the butt joint. It should remain leakproof even if solid particles (dirt), burrs, or slight corrosion create a small gap between the matching parts. The flange-like joint and the butt joint constitute very vulnerable seals inasmuch as they are easily affected by corrosion, dirt, etc.

However carefully designed, every joint should be tested, at least with a survey meter, to make sure that it is leaktight. The possibility of pores, blow holes, concealed cracks, or other defects in the material always exists.

X-Ray Collimators. The ideal collimator is a device that permits the entry only of those X rays that are designed to strike the sample inside the diffraction apparatus. Details of collimator design vary widely depending upon the factors discussed in the Introduction. However, most diffraction experiments are done by means of the pinhole collimator of the kind described here.

A schematic representation of specimen, pinhole collimator, and X-ray focus is given in Fig. 2. The working principle of the pinhole system is shown in Fig. 3. The first two pinholes (from right to left in Figs. 2 and 3) limit the size of the X-ray beam, and the third pinhole (nearest to the specimen) traps the X rays scattered from the edges of the beam-limiting pinhole #2. It is important that the third pinhole, called the scatter cap, does not touch the direct beam. Elimination or misalignment of the scatter cap will result in "parasitic" radiation that may interfere with the experiment (high and uneven background) or else escape into the environment.

It can be shown by simple geometry that the X-ray beam shaped by the pinhole system consists of two parts, the useful X-ray beam and the penumbra (Fig. 3). The former has an even intensity distribution throughout its cross section, whereas the latter constitutes the transition between maximum and zero intensity. The intensity gradient between the useful X-ray beam and the outer boundary of the penumbra is linear. The size of the penumbra as compared to that of the useful X-ray beam is critically dependent upon the distance between pinhole #1 and pinhole #2, or between pinhole #2 and the focus if pinhole #1 is omitted, which sometimes is the case.

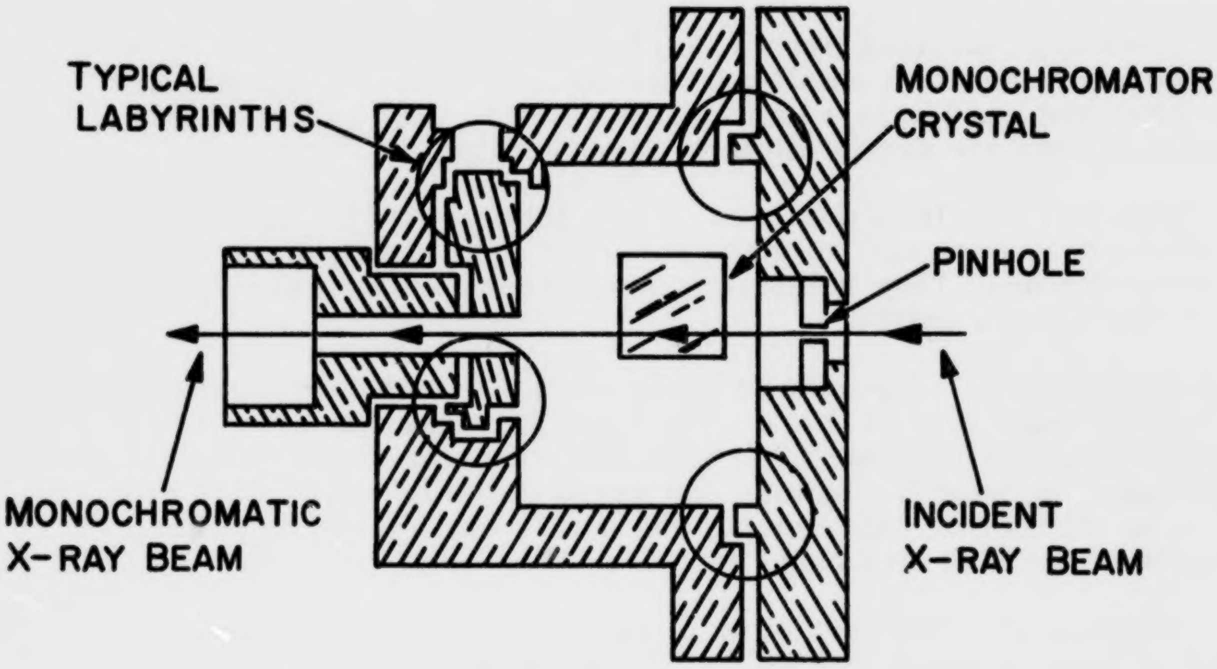

Fig. 1. Encircled are shown four typical labyrinth seals to prevent leakage of X rays from a monochromator housing. Each labyrinth eliminates any straight path from the interior of the housing to the outside.

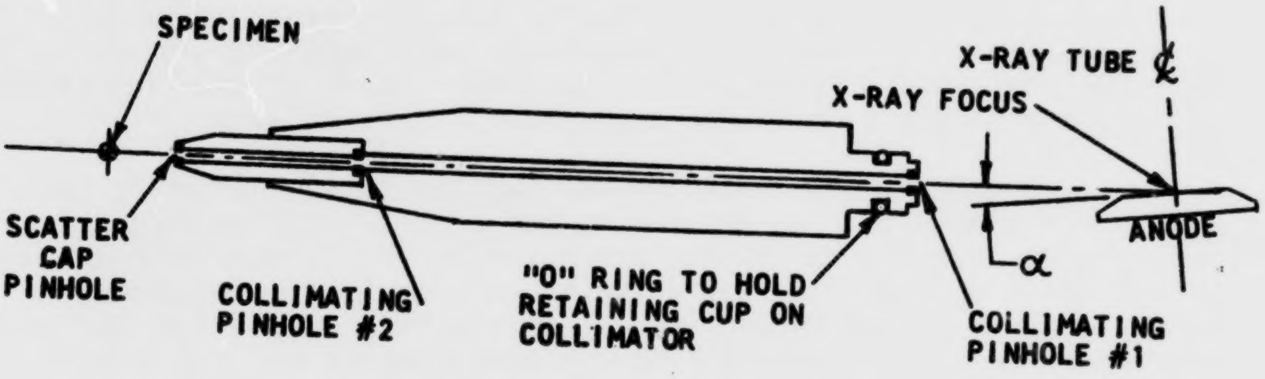

Fig. 2. A schematic representation of specimen (crystal), collimator, and X-ray focus.

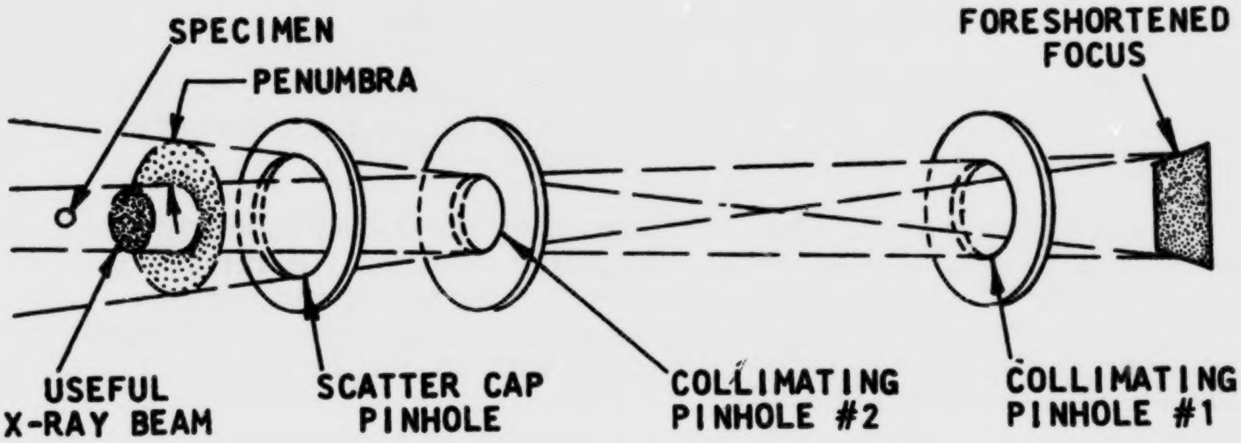

Fig. 3. The working principle of the pinhole system of an X-ray collimator. The pinhole system is enclosed, as shown in Fig. 2. Note that the X-ray beam consists of the useful beam and the penumbra.

It can be seen from Fig. 3 that pinhole #1 does not greatly affect the size and shape of the useful X-ray beam unless it vignettes the focus. The main purpose of pinhole #1 is to prevent the useful X-ray beam from coming into contact with the scatter-cap pinhole in the event that the X-ray focus is misaligned; that is, in case the center of the focus does not lie on the center line of the collimator.

A properly designed collimator confines all the X rays to the small useful beam and the penumbra, but slight scatter is caused by the media outside the collimator through which the X rays have to pass (air scatter, scatter from sample and mounting pin, fluorescence, Compton scatter, and diffraction). The secondary scatter usually is extremely weak and dissipates rapidly with distance because of its softness, great divergence, and high absorption in air.

For optimum performance of the diffraction apparatus (high signal-to-background ratio), a good designer should try to keep the penumbra as small and the pinhole support as rigid as is practicable. A good collimator is a precision device and should be handled with care.

It is seen that the collimator is not only a people protector but that it serves the purpose of obtaining at least a workable signal-to-background ratio. A collimator which is ill constructed or damaged so badly that it creates a safety hazard is, in most instances, bound to be useless for meaningful diffraction experiments.

Detailed information on collimators designed for a variety of special applications, such as low-angle diffraction and micro-focus techniques, can be obtained from the papers [1-11,14].

Collimator Couplings. The link connecting the X-ray tube with the collimator is referred to as the collimator coupling. A variety of designs have been described by Beu[12]. A more refined version designed by this author and constructed in this Laboratory's instrument shop is described below, together with an outline of some fundamental working principles.

The part of the collimator accommodating pinhole #1,* shown to the right of Fig. 2, is to be inserted into the collimator-retaining cup in front of the X-ray port, as is shown in Figs. 4 and 5. The small O-ring provides enough friction to avoid slippage and too easy a disengagement of the two parts.

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*This pinhole can be omitted; see preceding section.

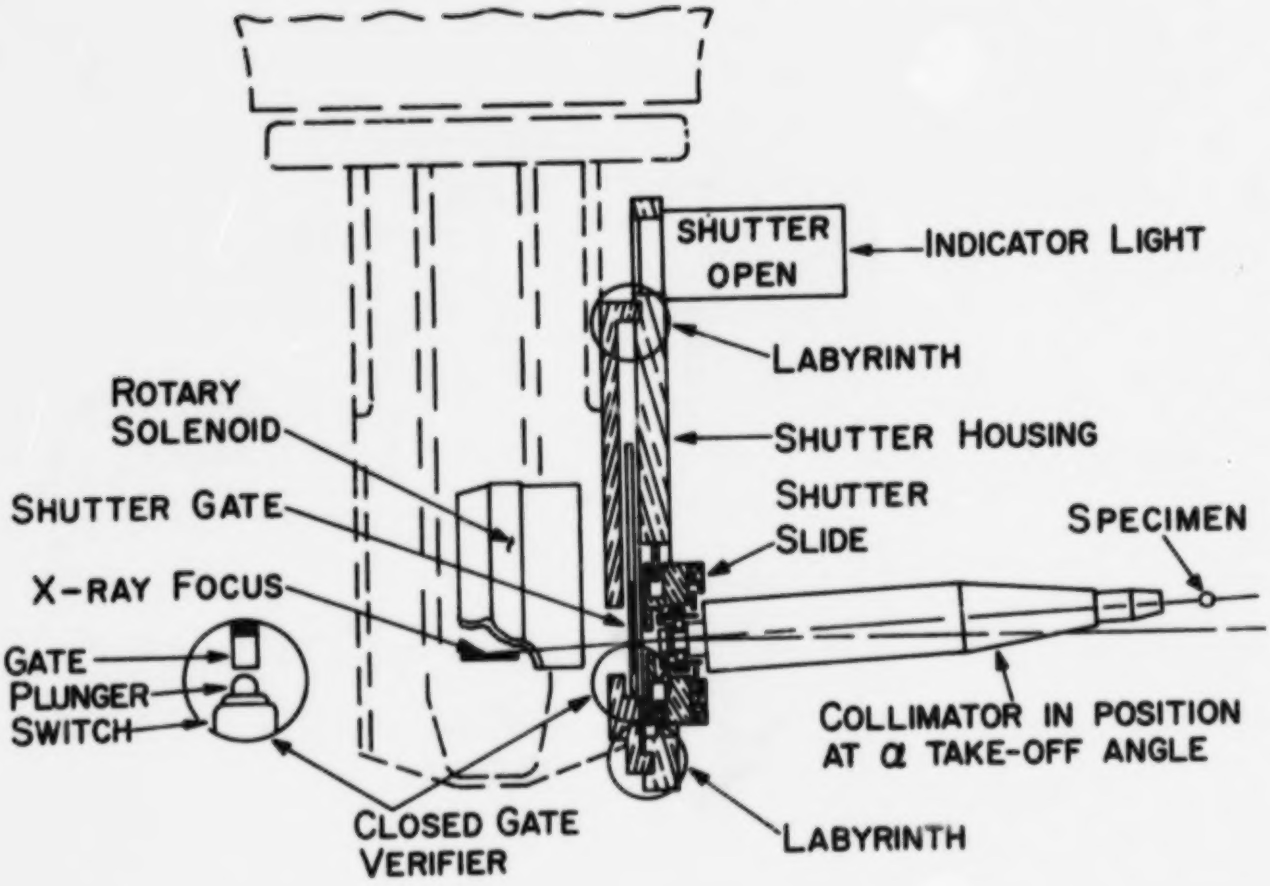

Fig. 4. Collimator and X-ray tube. An expanded, more detailed illustration of the collimator coupling including the shutter slide is given in Fig. 5.

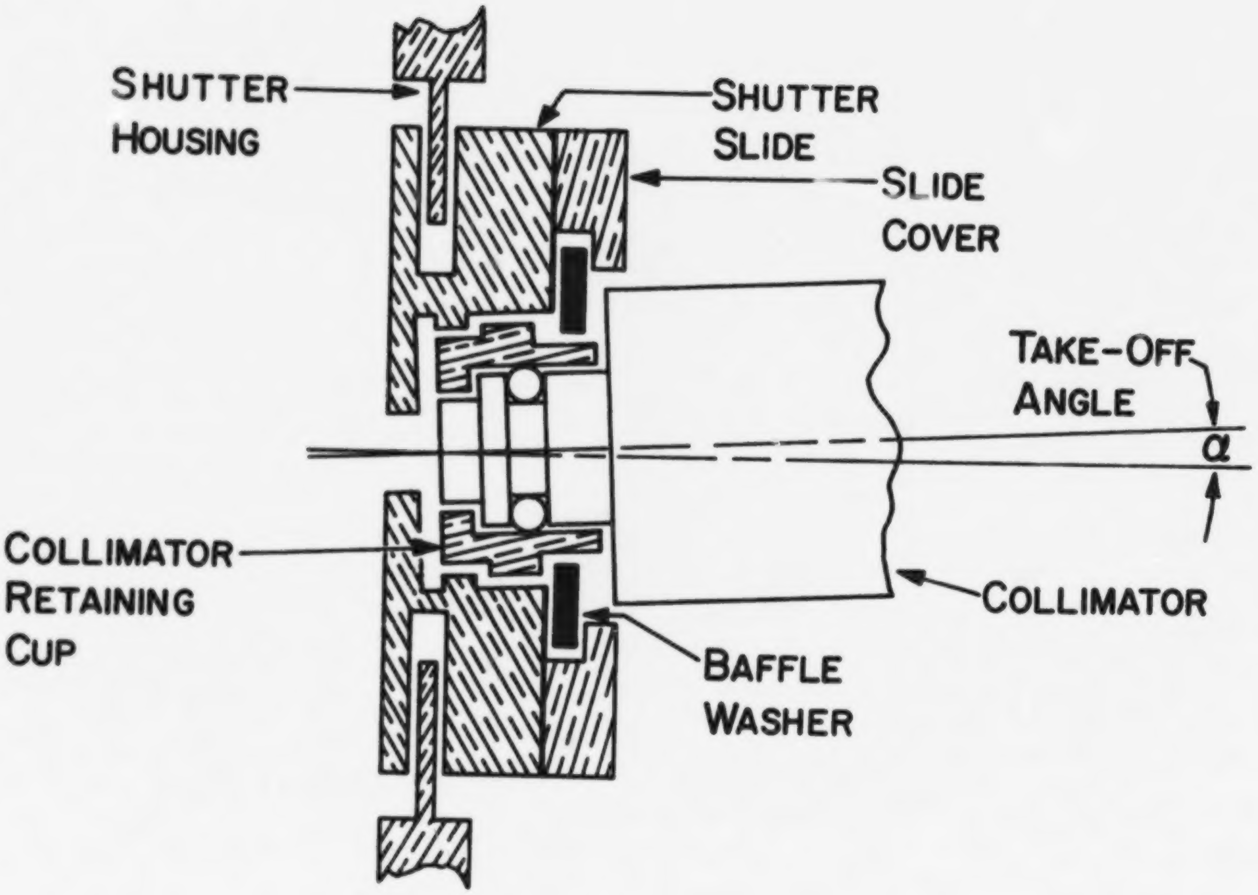

Fig. 5. A detailed description of the collimator coupling consisting of the shutter slide, the collimator retaining cup, and the baffle washer.

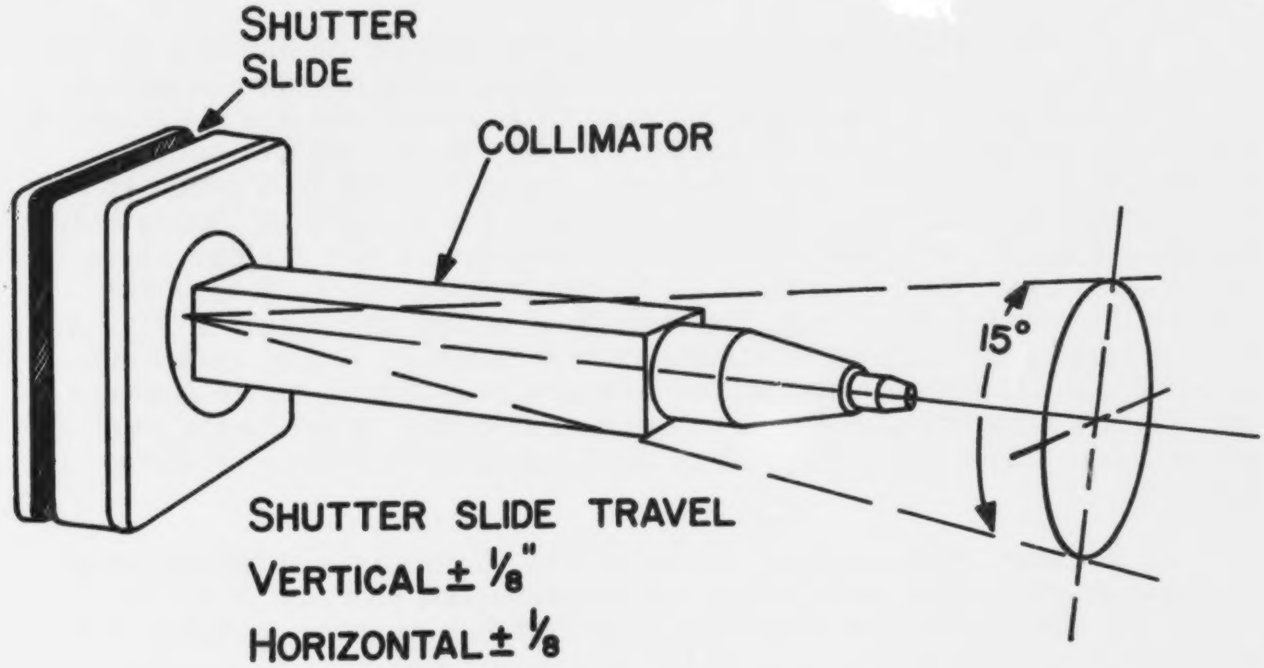

Fig. 6. The collimator coupling with the collimator in place. The shutter slide provides two translational motions of ±1/8 inch each, and the collimator can be pivoted within a cone of 15° aperture.

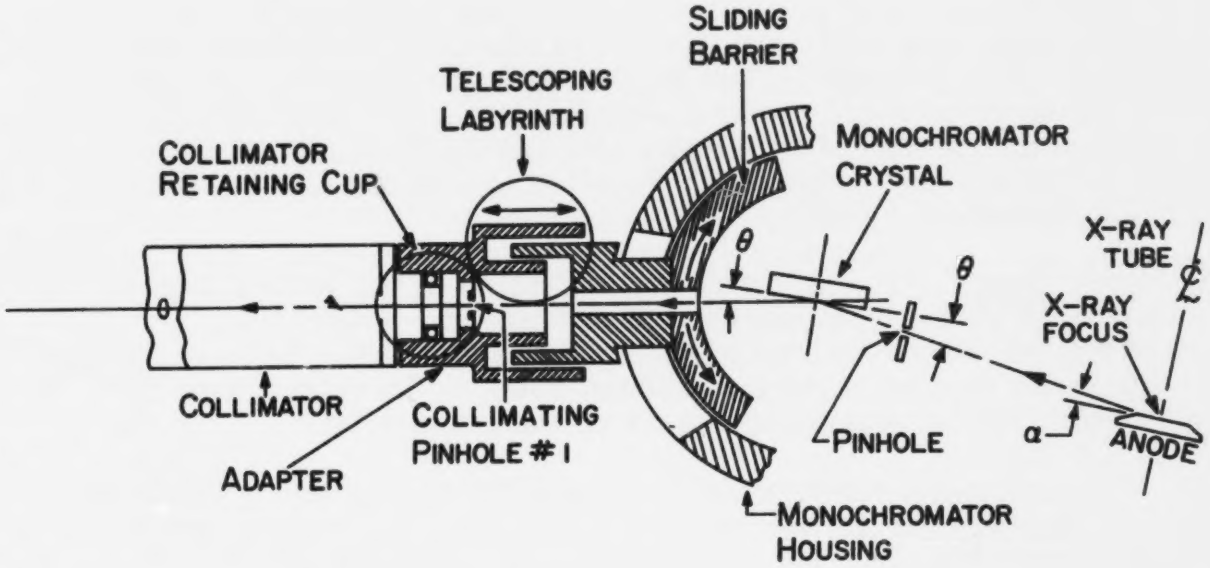

Fig. 7. A collimator coupling with a telescoping labyrinth applied to an X-ray monochromator.

For the satisfactory operation of the diffraction apparatus, the center line through the pinhole system should point toward the center of the X-ray focus. The angle between this center line and the plane of the focus, called the take-off angle (α), may be varied from one experiment to another. The coupling, therefore, has to provide an X-Y motion as well as an angular motion of the collimator, as is indicated in Fig. 6. Irrespective of the orientation of the various parts relative to each other, there is no X-ray leakage, because several labyrinths are incorporated, the details of which are shown in Fig. 5. It is seen that throughout the translational (shutter slide), rotational, and angular (retaining cup and baffle washer) motions, there never occurs any straight path for X rays from any part of the X-ray port to the outside. The more circuitous the labyrinth, the more efficient is the seal.

In short, the coupling shown in Fig. 5 consists of three parts: (1) the shutter slide permitting the translational motions of ± 1/8 inch each; (2) the collimator retaining cup affording angular motions of the collimator axis within a cone of 15° aperture, see Fig. 6; (3) the baffle washer providing the front seal and holding the retaining cup in place. The whole assembly, thus, acts as a flexible joint. It is important that sufficient latitude be provided for each motion in order to prevent collision before the focus goes out of view during alignment, especially when using the image caster described in a later section. One has to keep in mind that X-ray tube and collimator adjustments often are carried out in a darkened room.

A different kind of collimator coupling is shown in Fig. 7. Here, a telescoping labyrinth is used to couple a monochromator assembly to a collimator. The gaps inside this labyrinth are kept relatively large to avoid metal-to-metal contact. This arrangement provides some degree of flexibility and avoids the buildup of stress, should the parts move slightly in relation to one another because of thermal expansion.

The Beam Trap. Only a very small fraction of the direct X-ray beam is "used up" by the sample through diffraction, absorption, or both. Almost all the rays continue past the sample and have to be dissipated in such a way that secondary radiation does not interfere with the experiment. This is done by means of the beam trap.

A schematic representation of the beam trap and collimator is given in Fig. 8, and the mechanism of the trapping will be explained with the aid of Fig. 9. The trapping device consists of a hollow cylinder, the bottom of which is covered with a highly absorbent material such as lead, tantalium, or some other heavy metal. The direct X-ray beam, including the penumbra (see section: X-Ray Collimators), should touch the bottom of the cylinder only, not the wall.

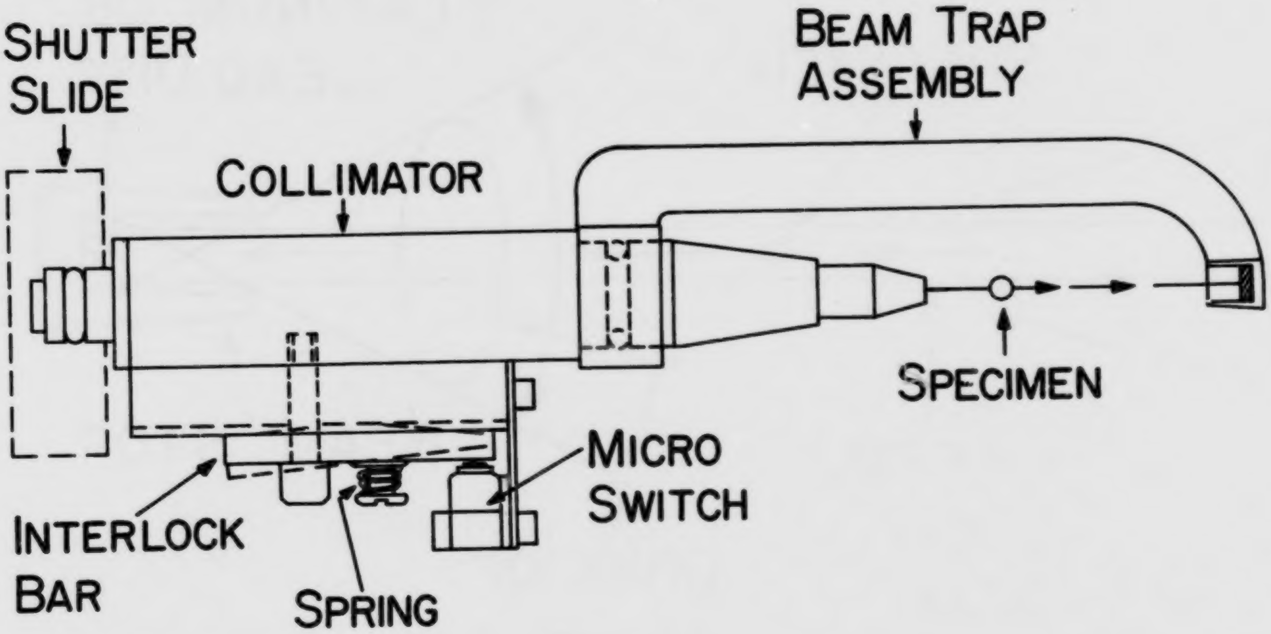

Fig. 8. Collimator and beam trap.

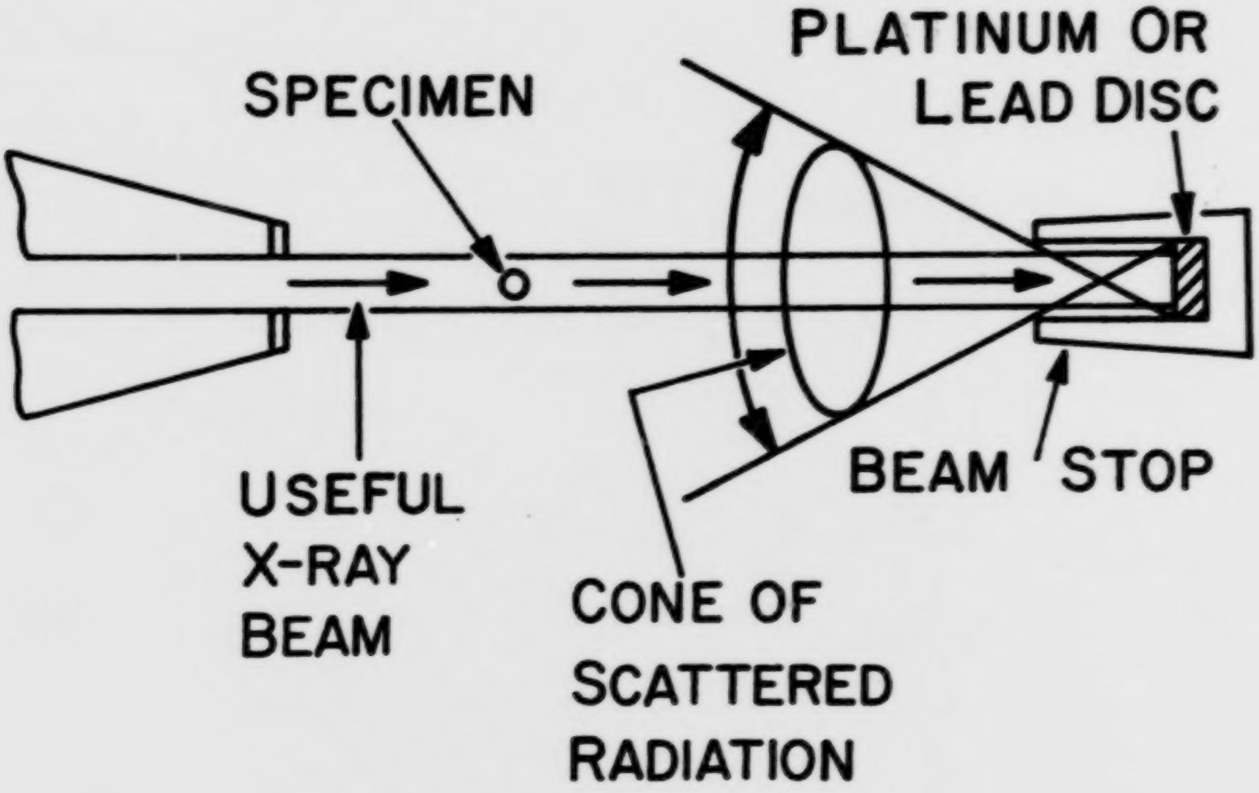

Fig. 9. The working principle of the beam trap. The aperture of the cone of scattered radiation is determined by the geometry of the trapping cylinder. The direct beam must not touch the cylinder wall.

The secondary radiation produced at the bottom is prevented by the cylinder wall from interfering with the diffraction experiment. It is seen in Fig. 9 that the aperture of the cone of secondary radiation is controlled easily by a well-designed trapping cylinder.

The aperture should be small enough to avoid interception of the cone of scattered radiation by the device that measures or records the diffracted beam; e.g., film, scintillation counter, proportional counter. Another important design factor is the blind angle the trap produces for the diffracted rays. This angle increases with decreasing distance between specimen and beam trap. On the other hand, at greater distance enhanced air scattering results. The various parameters have to be optimized to achieve a satisfactory performance of the diffraction apparatus. An excellent treatment of this subject has been given by Parrish and Cisney.[5]

Safety Shutters. Indisputably, the most suitable location for the shutter is as close as possible to the X-ray source; that is, immediately in front of the porthole of the tube and immediately behind the collimator coupling. The working principle of the shutter is simply to place a piece of highly absorbent metal (lead) in front of the port. This movable piece, the gate, is contained inside a leak-proof compartment attached directly to the face of the tube, with appropriate labyrinths to ensure that the joints are leaktight.

Many modern automatic diffractometers activate the shutter electrically with the use of a computer-controlled solenoid. The shutter is open only during periods of measurement and closes as soon as other kinds of operations are performed, such as changing the orientation of the specimen crystal and repositioning the counter.

The design of a fail-safe automatic shutter is not as simple a matter as it might first appear. One has to keep in mind that the shutter may be activated a thousand times a day over long periods of time and that a single failure may result in loss of precious data-collection time if the apparatus is left unattended during the operation.

During manual operations, such as sample installation, crystal alignment, repairs, and adjustments, the operator has to be kept informed continuously as to whether the X rays are on or off or the shutter is open or closed. This is most often accomplished by means of warning lights. These must be devised such that lamp failure will cause the generator to turn off or the shutter to close. To avoid reliance on springs, the shutter gate should close through the action of gravity as soon as the power to the solenoid is cut off. Since the shutter gate can jam, leaving the port partially open, there must be a positive verification that the gate is properly seated in front of the port. The gate then turns off a warning light that has to be operable before the X-ray generator can be activated.

For the computer-controlled, automatic shutter operation two verifications are desirable: (1) fully open (for meaningful data collection); and (2) fully closed (for safe manual operation). Any intermediate position of the gate (caused by a jam) should cause the automatic data collection to stop, but a warning light should stay on unless the X-ray generator is off.

In the case where the shutter indicator light is in series with the shutter solenoid and the power is supplied by the computer interface (independent of the X-ray generator), the following four cases have to be taken into account:

Case	Power from Interface	Warning Light	State of Shutter	Remark
1	O.K.	ON	Open	Data collection
2	O.K.	OFF	Closed	Safe
3	Failure	OFF	Closed	Safe
4	Failure	OFF	Jammed	Unsafe

It is seen that this arrangement may give the operator a false sense of security, and that case 4 must not be permitted to occur.

A schematic representation of a safety shutter designed and constructed in the author's laboratory is given in Figs. 4 and 10. The shutter gate is activated with a rotary solenoid of 25° operating angle. Straight solenoids were found to be unsatisfactory. The shutter gate is enclosed in a leakproof housing, and each joint is in the form of a labyrinth (indicated in Fig. 4). The gate closes through the action of gravity. The indicator light is turned off if the lower part of the gate hits the plunger of a microswitch, which is referred to in Fig. 4 as the "closed-gate verifier". A second microswitch, shown in Fig. 8, deactivates the shutter solenoid if the collimator-retaining screw is loosened. Lamp failure will cause the solenoid to be deactivated.

A thorough analysis is of all possible alternatives indicates that an absolutely fail-safe shutter system does not exist if reliance is to be placed entirely on indicator lights. No matter how much redundancy is built into the electronic or electromechanical system, the possibility of a failure (relay failure, sticking contact, etc.) always exists.

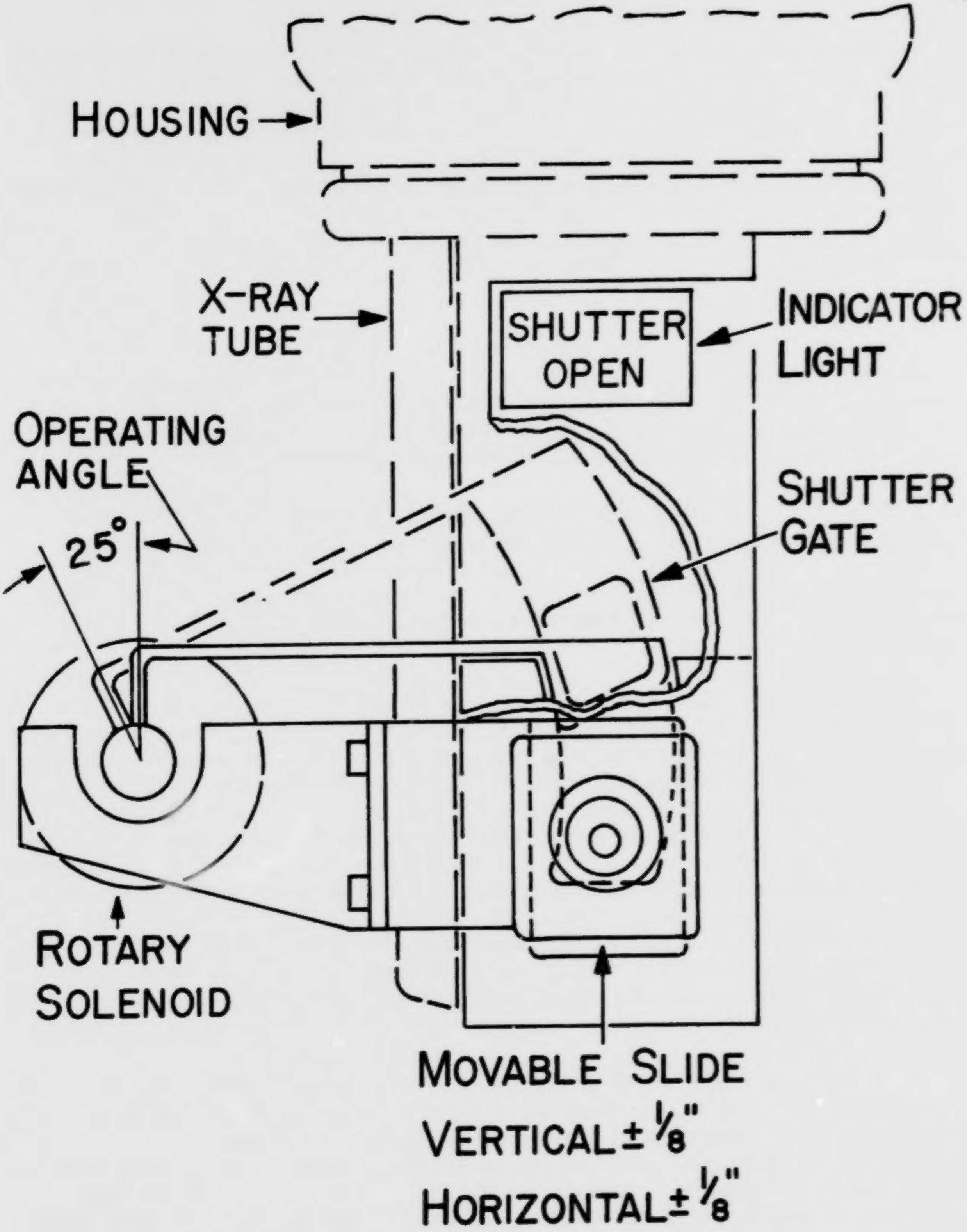

Fig. 10. Schematic representation of X-ray tube and safety shutter. Some details of this shutter are shown in Fig. 4.

A non-automatic, so-called self-closing shutter quite frequently used in laboratories throughout the country is shown in Fig. 11. This shutter is most often used in conjunction with photographic diffraction equipment. Here, the camera has to be moved from the X-ray lab to the dark room for loading and unloading the film, each time disengaging and reinserting the collimator into the coupling. The shutter is leakproof if properly used, as shown in Fig. 11c, but if the collimator is partially engaged, as shown in Figs. 11a and b, it prevents the sliding gate from closing and leakage occurs underneath the collimator.

No matter how well a safety shutter is designed, the best assurance against X-ray exposure is to be alert and properly trained. It is good practice to count to ten before pushing the X-Ray ON button and in the meantime inspect the system. Warning lights are useful, but they should not be trusted when they are OFF.

Alignment of the X-Ray Focus (The Image Caster). An important point at issue concerning X-ray safety is the ease and comfort with which a diffraction apparatus can be aligned relative to the X-ray focus. The system is aligned when the center line through the pinhole system of the collimator points toward the center of the focus at the proper take-off angle α.

In conventional, sealed-off X-ray tubes the focus is a planar rectangular area, the size of which depends upon the make and model of the tube. Common sizes are about 0.8 mm × 15 mm and 0.8 mm × 10mm. If the 15 mm-long focus is viewed end on by the crystal (through the collimator) at a take-off angle $\alpha = 3^\circ$, a foreshortened area of 0.8 × 0.79 mm is seen. In case of the 10 mm-long focus, the same area is seen at $\alpha = 4.5^\circ$, see Fig. 12. The choice of the length of $\overline{RS}$ (= source length × sin α) in Fig. 12 depends upon the specific kind of diffraction experiment to be conducted. For special, less common experiments extremely fine foci are used (small-angle scattering, microfocus techniques of various types; see paper [1, 2, 4, 6]). One of the most outstanding and pioneering papers on X-ray foci and their use has been written by Huxley.[14]

A method often used to align the X-ray focus relative to the collimator is to view the beam on a fluorescence screen placed in front of the collimator and translate the tube until "maximum intensity" is obtained. A lead glass shield of appropriate thickness, then, has to be placed between the viewer and the screen! A fine adjustment of the focus is sometimes made subsequently, either with the use of a special slit system in front of the counter-tube (when using a diffractometer) or with other cumbersome and time-consuming manipulations involving the specimen crystal.

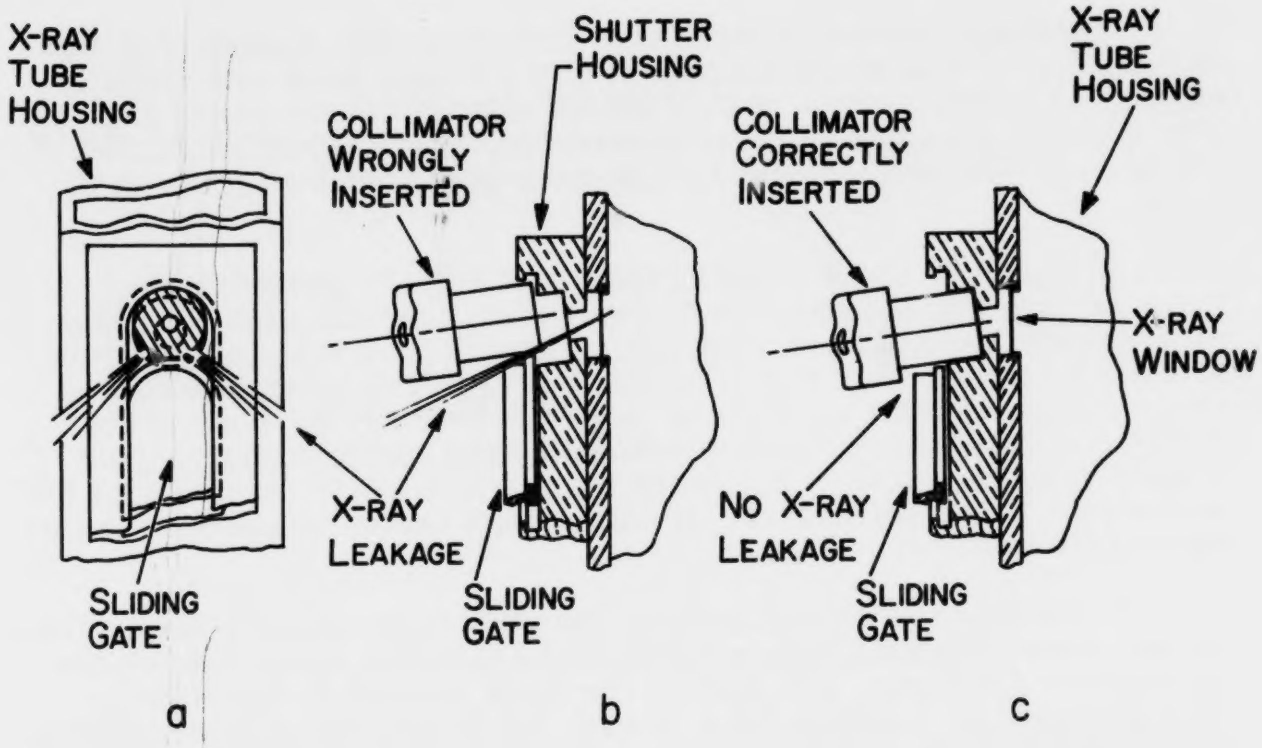

Fig. 11. A so-called self-closing shutter. (a and b) X-ray leakage occurs if the collimator is partially inserted. (c) Collimator is properly inserted.

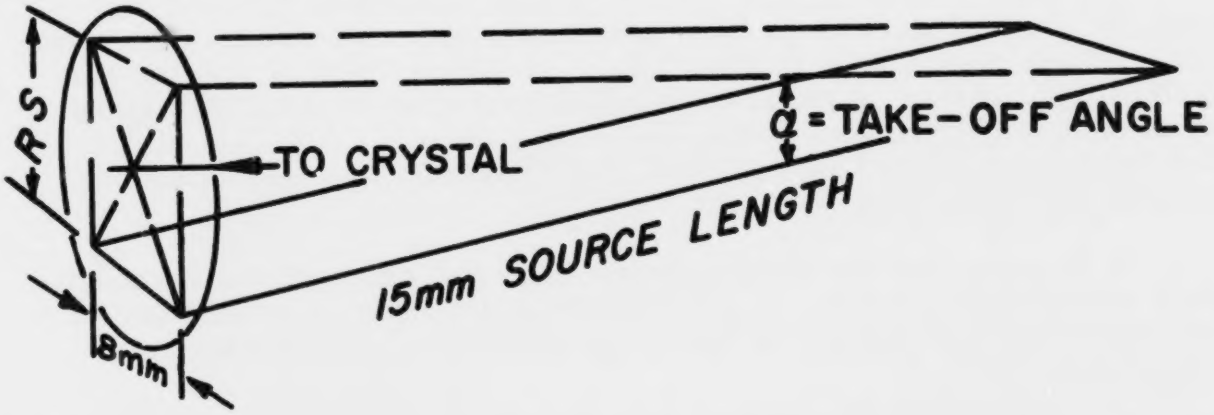

Fig. 12. Foreshortened X-ray focus as seen by the crystal at take-off angle α. The length RS is dependent upon α.

Whereas, the use of the Image Caster, a tool developed at this Laboratory,[13] makes the alignment of the X-ray focus significantly easier. A cross-section of this device is shown at the top of Fig. 13. The working principle (central part of Fig. 13) is the same as that of the camera obscura, invented around the year 1500 by Leonardo da Vinci.

The pinhole to the right at the top of Fig. 13 produces an inverted image of the focus on a fluorescence screen (left of figure). Immediately behind the screen is a tungsten cross hair, and in front of it a lead-glass disc to protect the viewer. The outer dimensions of the image caster should correspond very closely to those of the X-ray collimator, and the line connecting the center of the pinhole (right) with the center of the cross hair (left) should coincide with the center line of the collimator when the image caster is inserted in the collimator bracket.

If the focus is viewed end on, the pinhole produces a trapezoidal image superimposed on the shadow of the tungsten cross hair on the fluorescence screen. The part of the focus closest to the pinhole (line through the points 3 and 4 in Fig. 13) is magnified more than the part farthest from it (line through 1 and 3). The magnification is determined by the ratio between the two distances, fluorescence screen-to-pinhole and focus-to-pinhole. Hence, the shape of the trapezoid depends upon the length of the focus, the take-off angle, and the magnification factor.

The smaller the pinhole diameter, the better is the definition of the image although it is weaker. A suitable pinhole diameter is 0.4 mm drilled through a platinum disc of 0.75 mm thickness.

To align the focus, the X-ray tube is translated and rotated until the trapezoidal image is symmetrical and centered on the cross hair. The image shown in Fig. 13b is obtained when the center line of the image caster is parallel with the long side of the rectangular focus (vertical tube) and points toward its center. Rotation of the (vertical) tube around its cylinder axis produces the unsymmetrical images shown in Figs. 13a and c.

It is seen that the image caster is useful not only for the alignment of the X-ray focus; it affords simultaneously an evaluation of the suitability and quality of the focus as far as its geometry is concerned.

Temporary X-Ray Shielding. A frequent sight in X-ray laboratories is lead sheet or foil placed around parts of X-ray diffraction equipment to shield off leaks occurring around collimator couplings, tube shields, etc. Although in most cases such shielding is effective, the

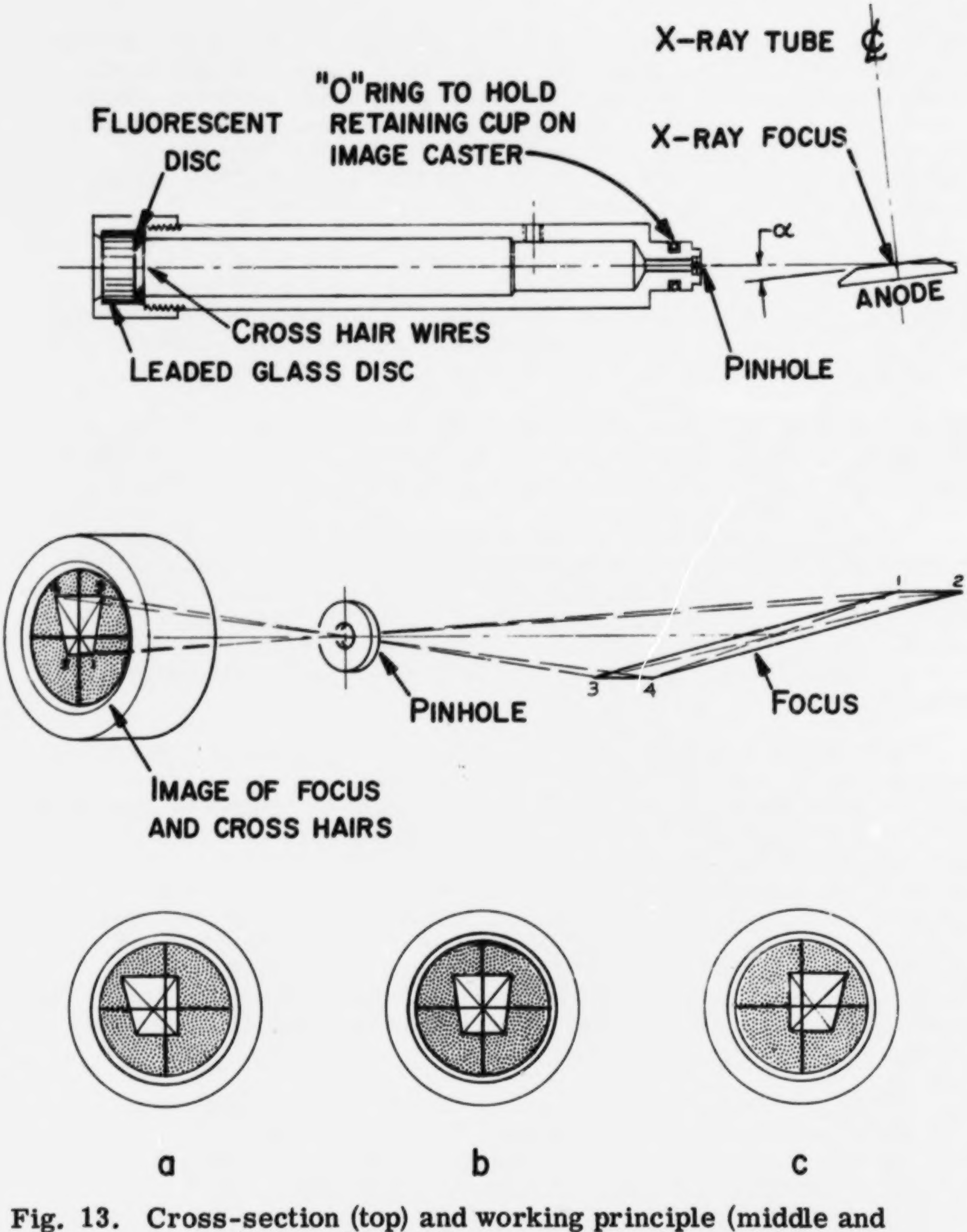

Fig. 13. Cross-section (top) and working principle (middle and bottom) of the Image Caster used to align quickly and safely the X-ray focus relative to the collimator. The center line through the Image Caster should coincide with that through the collimator. Image Caster and collimator should be commensurate and interchangeable.

disadvantage is that its proper place cannot always be readily identified once the shield has been removed. This problem may become severe in laboratories where changes in personnel (students, postdoctoral fellows) occur frequently, and a newcomer cannot communicate with the lead-shield "designer". It seems that improvised shielding frequently is the result of improper engineering. Often, too shallow a labyrinth is used in a collimator coupling.

The designer of X-ray equipment has to be aware of the difficulty of obtaining a permanent X-ray seal by joining together flat surfaces. Many a designer will become disappointed with the performance of his shielding device unless he is aware of the importance of the labyrinth described in the section on Leak-Proof Joints.

General Design Features that Help to Prevent Accidental X-Ray Exposure. One of the most critical operations as regards accidental exposure to X rays is the alignment of the diffraction apparatus.

Almost any user of a single-crystal X-ray diffractometer is confronted with the problem of determining the zero settings of 2θ, ω, and χ and of bringing the X-ray focus into alignment. A method that avoids the multiparameter problem of finding the proper settings with the aid of X-ray reflections from a single crystal that, in turn, is to be aligned simultaneously, has been described by Samson and Schuelke.[13]

The effort required to align a diffraction apparatus depends largely upon the design details of the adjustable parts and upon the quality of workmanship. A general rule of proper design is that each parameter be adjustable independently of the others in a straightforward manner by no more than one operation. Thus, to adjust the height of the collimator centerline relative to the X-ray focus by changing the height of the diffraction apparatus, usually requires the setting of three height-adjustment screws. These simultaneously determine the tilt of the apparatus, and we are confronted with a multiparameter problem. In contrast, provision of a z-motion on the tube support requires a single, straightforward operation, but only if the guides are straight and tight.

To facilitate easy adjustment of the diffraction apparatus relative to the X-ray focus requires: (1) X, Y, Z motion of the X-ray tube; (2) ample X, Y translation of the shutter slide (Figs. 4, 5, 6); (3) ample flexibility of the collimator coupling (Figs. 5, 6, 7); (4) sufficient depth of the labyrinth of the collimator coupling to avoid de-coupling; (5) provisions of all translational and pivoting motions should be of sufficient latitute to avoid jamming before the X-ray focus comes out of view of the image caster (Fig. 13); (6) all adjustment knobs should turn easily so as to make it possible to feel resistance, should jamming or collision of parts occur.

ACKNOWLEDGMENTS

I thank Mr. Ronald Wiggins and Mr. Richard Ehrich for preparing the figures. Mr. Richard Ehrich and Mr. William W. Schuelke have made valuable contributions to the design of the equipment described here. I thank Mrs. Joy Hays for proofreading the manuscript and for helpful comments. Part of the work described here was supported by Grants GP-4237, GP-7984, and GP-17504 from the National Science Foundation.

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DISCUSSION

HELEN PROCTOR (PICKER): I should like to mention that the problem of beam trapping is an important one. I am glad that you brought up the geometrical considerations.

There is one other simple thing that you can do to reduce the amount of back scatter. That is to use a layered beam trap. You could use combinations, for example, of lead, copper, and aluminum. Aluminum and copper will absorb the fluorescence of the lead.

DR. SAMSON: That is correct. You have a weakly absorbing material at the top; for instance, aluminum. A heavy metal, say lead, tantalum, or platinum, is at the bottom of the trap. The direct x-ray beam penetrates the aluminum and is absorbed by the heavy metal. The fluorescence radiation emitted by the heavy metal is much softer than the incoming radiation, and, therefore, is readily absorbed by the aluminum. This is what we refer to as the laminated trap.

RADIATION SAFETY AND X-RAY DIFFRACTION TECHNIQUES

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1. INTRODUCTION

To each of the three groups, health physicists, users, and manufacturers, there are different things to be said about providing radiation safety in diffraction equipment. To the health physicist, I wish to stress that the variety of experimental equipment configurations is too great to permit a single solution of general acceptability. Flexibility, even fluidity, of equipment configuration is of paramount importance, particularly in new applications and in development of new techniques. To the user, especially the diffractionist, I wish to make the point that incorporation of radiation safety devices and procedures in your experimental approach need not be too bad, nor too onerous. Such incorporation is merely another boundary condition to be included in the initial experimental design. To the manufacturers I would say that the rising concern with radiation safety and the need for radiation safety devices simply provides you with the opportunity to sell more equipment, so you really have nothing to worry about - except that I notice you do keep looking back over your shoulders to see if Ralph Nader is gaining on you!

The first part of this paper, then, will be devoted to an elaboration of the points we wish to make concerning the variety of useful and desired experimental configurations and their need for flexibility. The second part will be devoted to a discussion of some possible acceptable solutions to the process of providing a radiation-safe operation. (Parenthetically at this point, we wish to stress the need for acceptable solutions. Unacceptable solutions are all too readily offered by people who are not users. For example, I know of one case where it nearly became the legislative rule that the shutter and x-ray tube were to be so interlocked that the x-rays were turned off at any time the shutter was opened. This seems akin to the practice of the librarian who feels that the only proper place for a book is on the shelf.)

2. VARIETY OF EQUIPMENT CONFIGURATIONS AND RADIATION SAFETY PROBLEMS

2.1 Selection of examples

To make the point about variety of configurations, we shall select our examples, illustrative only and not comprehensive, from the field of x-ray diffraction. In part we make this choice because, generally speaking, it seems that the radiation sources and scatterers are generally better contained and shielded in x-ray flourescence analysis apparatus. Perhaps that is because the scattered radiation level would tend otherwise to be higher and, therefore, more attention has been given to that apparatus in the past.

2.2 Common features of x-ray diffraction experiments

In spite of the variety, certain common features of diffraction techniques can be usefully identified. Operations that are common to a great variety of diffraction techniques include (i) specimen position control, (ii) specimen environment control, and (iii) equipment-repair and modification operations. Specimen position control includes sample alignment, which involves both a visually controlled step and one which requires the use of x-rays, and the frequent need for checking and, possibily, changing the sample alignment during the course of the experiment. Specimen environment control involves the necessary devices for controlling the specimen temperature (both high and low), pressure up to as much as 100 kilobars, electrical field, ambient atomosphere, and other features. Some of these devices will be illustrated here.

Similarly, from a radiation safety standpoint, most experimental apparatus for diffraction have certain common weaknesses on the "down stream side" (in the sense of the x-ray flux) of the collimator. These are primarily the beam stop and beam obstructions. Beam stops are often impermanent, for experimental convience in setting up the apparatus, and in consequence are sometimes missing or improperly replaced. Further, a simple beam stop gives excessive back scatter; a properly designed beam trap is needed and is, in present practice, rarely provided. Even some commercial apparatus of today does not provide a beam trap but, simply, a beam stop. Obstructions commonly occur in the beam in the form of sample apparatus and beam reducers. "Sample apparatus" includes holders, containers, electrical leads, etc. "Beam reducers" includes slits, apertures, accidental obstructions, etc.

2.3 "Standard"diffraction techniques

2.3.1. Single crystal diffractometry. In illustrating the variety of the equipment configurations, we look first at the area of "standard" single-crystal diffractometry. Here the specimen is a small crystal completely

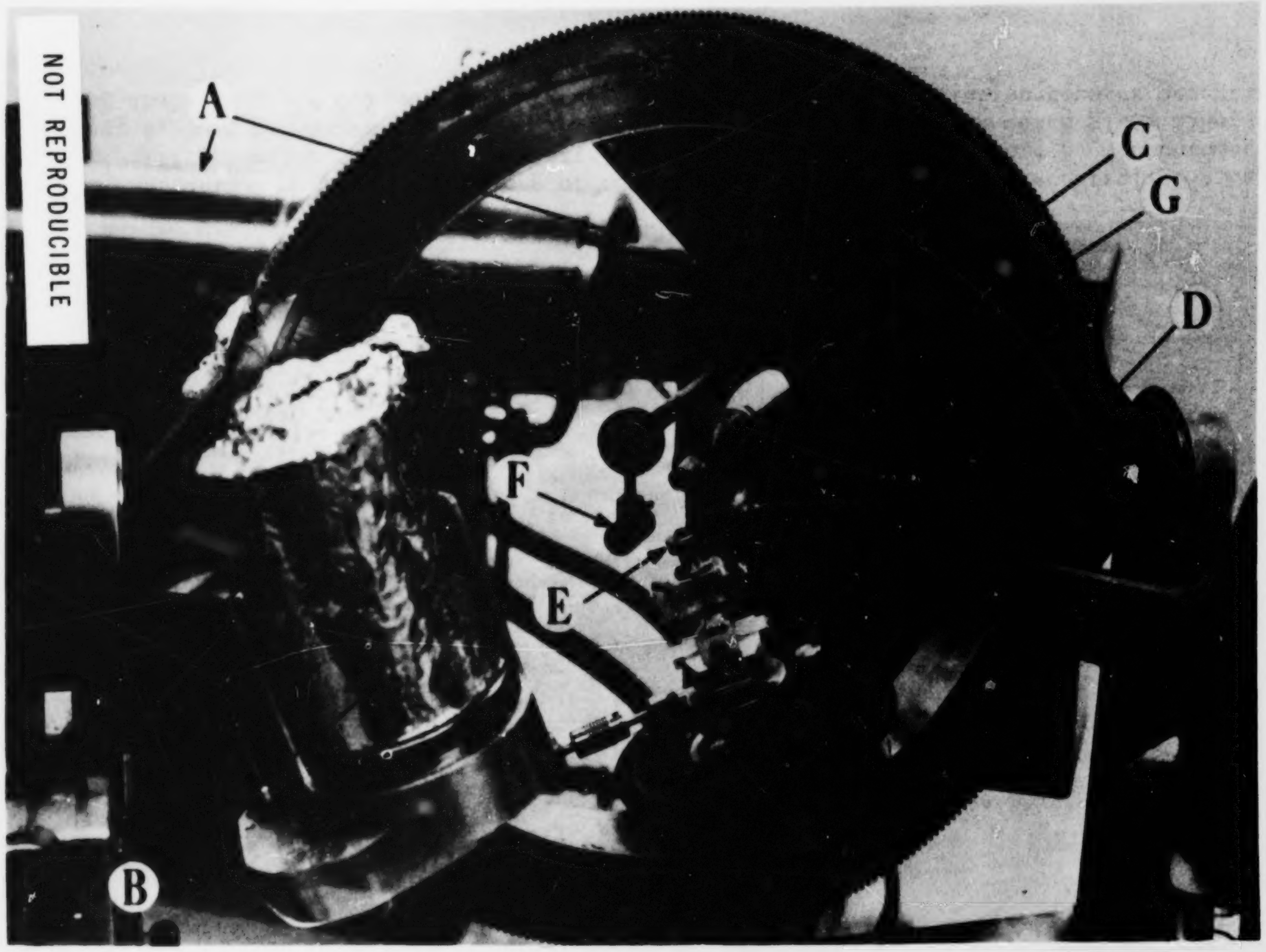

Figure 2. Principal mechanical portions of punched-tape controlled single-crystal diffractometer. Some of the parts are: A, x-ray tube and housing; B, shaft-encoder and servo motor (wrapped in conducting foil to provide collision-sensing capability); C, beam collimator; D, detected-beam tunnel; E, brass plug on which glass fiber holding small (e.g. < 0.5 mm dia.) specimen is mounted; F, beam trap suspended on a pendulum to permit D to pass through $2\theta=0$ position; G, condical lead shield used to stop direct x-ray beam when beam trap is held aside by detected-beam tunnel.

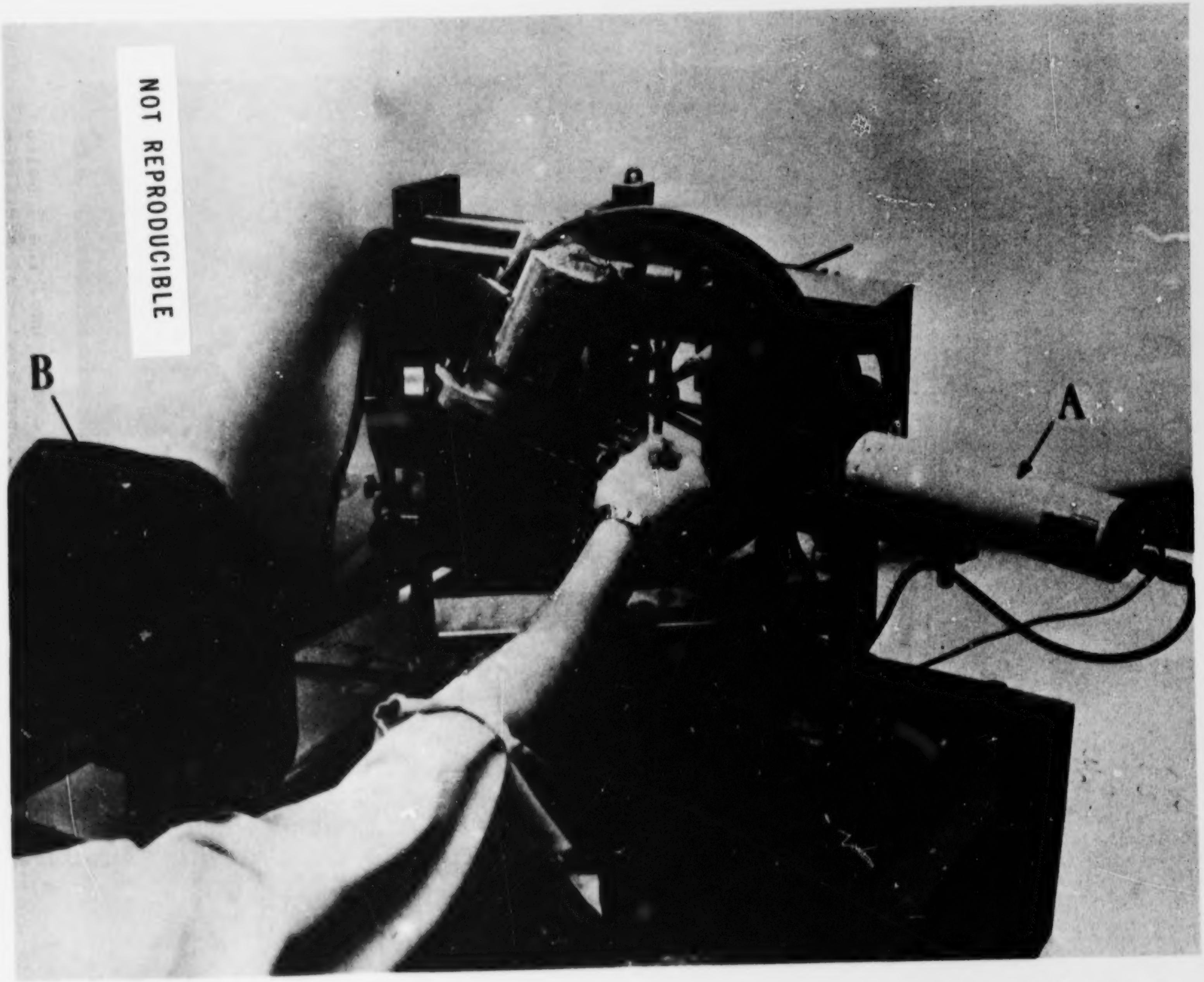

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Figure 3. Hand position during cyrstal alignment on instrument in Fig. 2. "A" is the scintillation-counter detector; "B" is a permanently-mounted back-up beam stop.

bathed in the x-ray beam. Fig. 1 shows the specimen and diffractometer in what is, from the radiation safety point of view, the easiest case to handle; it happens that this particular diffractometer is under computer control. Because of that, it is not necessary that the crystal be carefully aligned with the use of x-rays unless alignment done elsewhere (of the crystal on the goniometer head) is not sufficient. Therefore the operator need never reach into the area near the specimen and all operations can be controlled remotely from the computer console. The only problems that might arise in this case are those of the poorly designed beam stop and of Bragg reflections, from the specimen, other than the reflection being monitored by the detector. As Kehl has pointed out in the first paper, these "extra" Bragg reflections may have intensities as high as 80 roentgens per hour. However, an individual reflection operates for only a very short time and the operator does not necessarily stay in the vicinity continously.

A slightly more difficult case is illustrated in Fig. 2. This unit is automated, but is not computer-controlled. In this case the beam stop is a well-designed beam trap which operates well unless the counter position is near $2\theta=0$. In that case, the pendulum holding the beam trap is shoved aside and the beam hits the conical lead shield on the detected-beam tunnel. At those positions of the detector, then, there will be some back-scattered radiation from this simple beam stop. Potential radiation-safety problems arise in two other ways. The first is that the x-ray tube and the collimator are not mechanically interlocked in a manner such as Professor Samson (paper No. 4) has suggested. Further, one-of-a-kind instruments, such as this is, tend to have their parts more readily movable, and demountable, than do commercially made instruments. For alignment of the instrument currently to provide optimum performance this can be an advantage; from the standpoint of certain preservation of a given alignment, and consequently a suitably radiation-safe assembly, it can be a disadvantage. The second potential hazard arises because of the need for the crystal specimen to be finally aligned with the x-ray beam ON. Fig. 3 shows the nature of the difficulty. It is necessary that the operator's hand come close to the beam where, with careless action, it could wander into the beam. Since it is often necessary, for other reasons, that the beam path not be entirely enclosed, it is obvious that radiation safety in this case will depend in part on the operator knowing what he is about.

2.3.2. Powder diffractometry. One of the standard powder diffractometers is shown in Fig. 4. This is a familiar sight to most people here because this type of diffractometer has been on the market for nearly 20 years and there are a great many of them in the field. With this instrument there is a tendency for the radiation scattered through the open top of the radiation shield to be rather large. Further, when the counter arm is moved to the negative position there is no beam stop. Moreover, on some of the older instruments, at least, the beam stop provided is too thin for use with molybednum radiation.

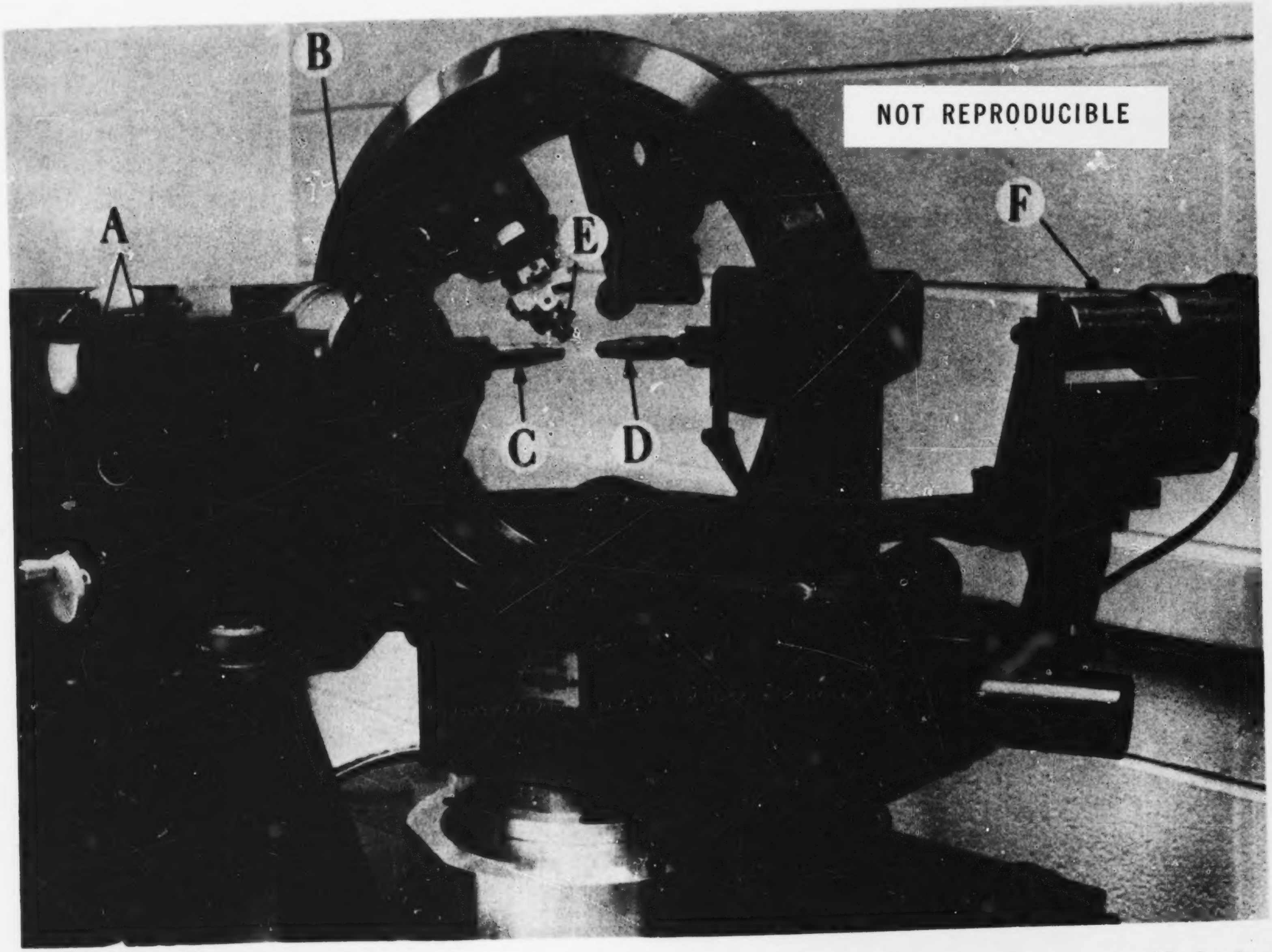

Figure 1. Principal mechanical portions of commercially available computer-controlled single-crystal diffractometer. Some of the parts are: A, x-ray tube and housing; B, monochromator housing; C, beam collimator; D, detected-beam tunnel; E, brass plug on which glass fiber holding small (e.g., < 0.5 mm dia.) specimen is mounted; F, scintillation-counter detector.

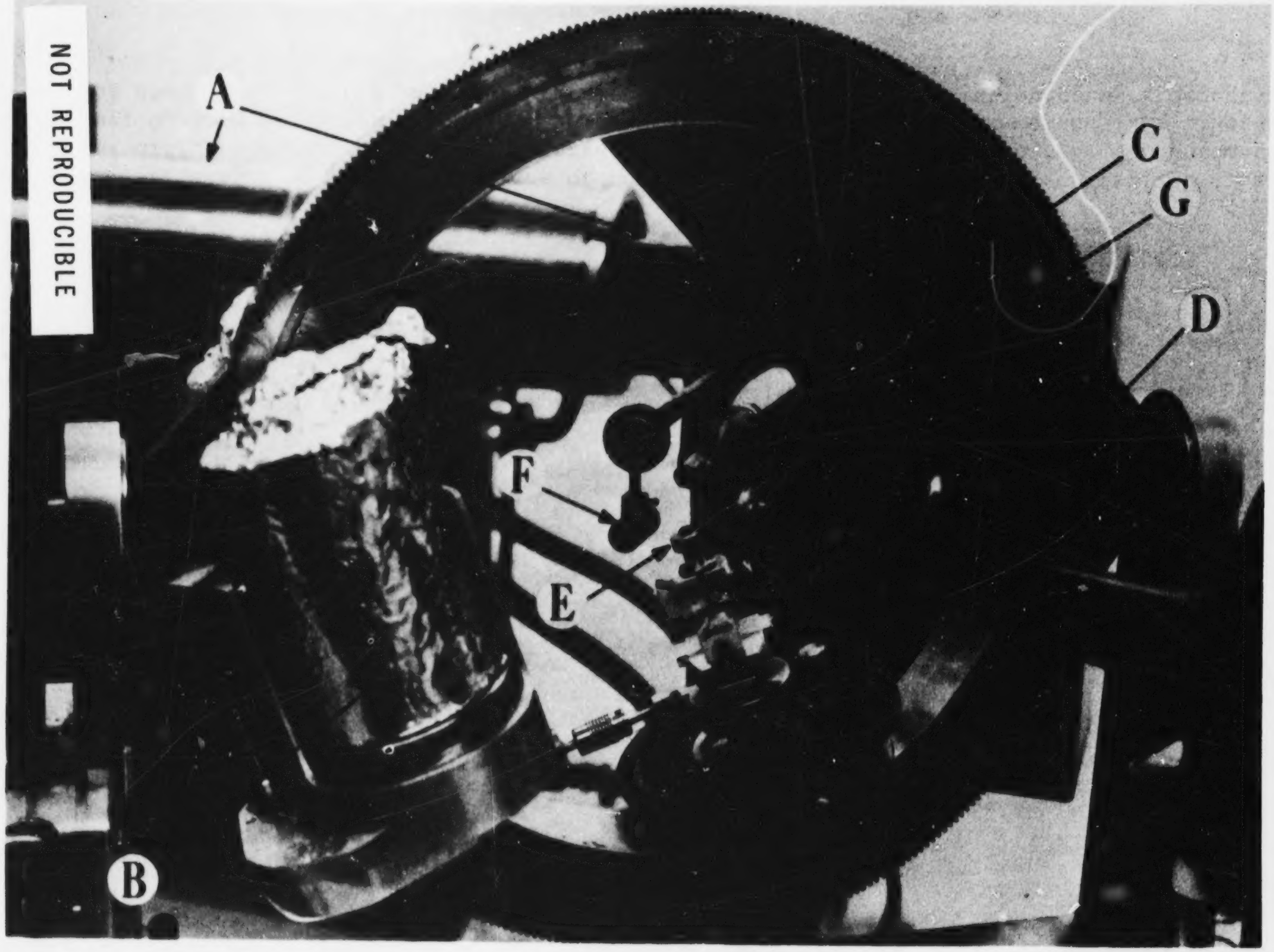

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Figure 2. Principal mechanical portions of punched-tape controlled single-crystal diffractometer. Some of the parts are: A, x-ray tube and housing; B, shaft-encoder and servo motor (wrapped in conducting foil to provide collision-sensing capability); C, beam collimator; D, detected-beam tunnel; E, brass plug on which glass fiber holding small (e.g. $<$ 0.5 mm dia.) specimen is mounted; F, beam trap suspended on a pendulum to permit D to pass through $2\theta=0$ position; G, condical lead shield used to stop direct x-ray beam when beam trap is held aside by detected-beam tunnel.

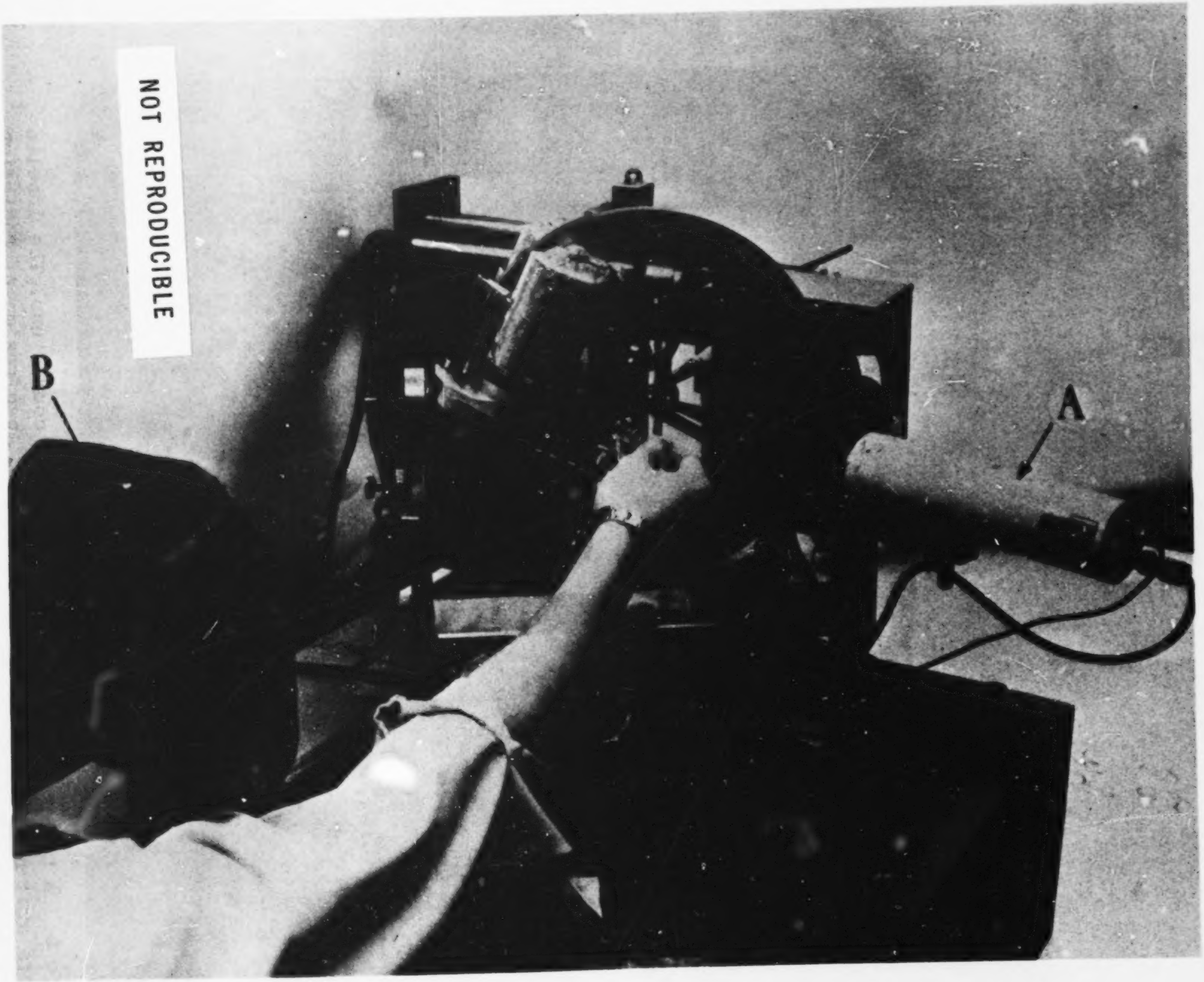

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Figure 3. Hand position during cyrstal alignment on instrument in Fig. 2. "A" is the scintillation-counter detector; "B" is a permanently-mounted back-up beam stop.

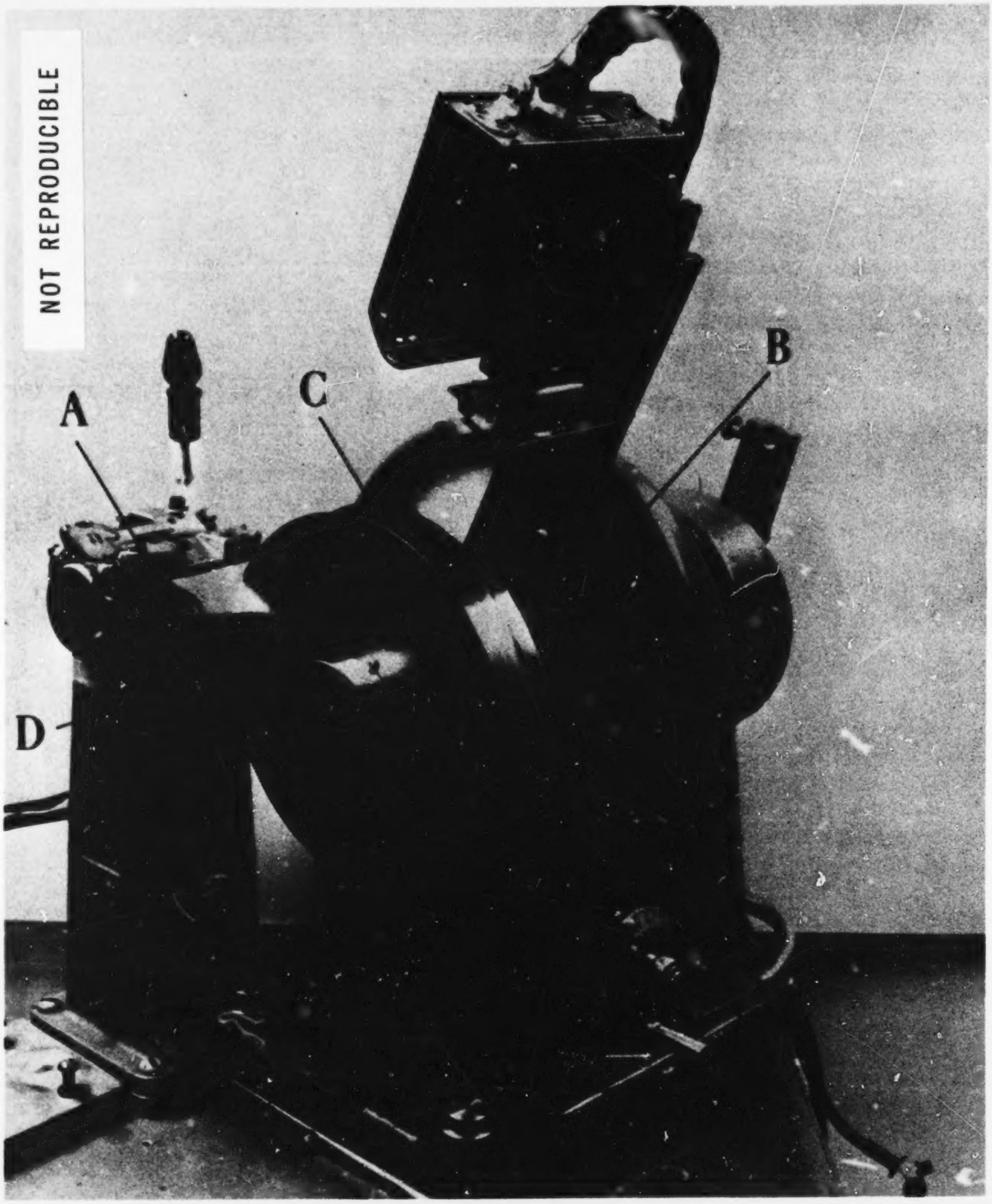

Figure 4. A type of powder diffractometer in common use. The labeled parts are: A, x-ray tube; B, beam stop; C, open region of radiation shield, D, from which scatter occurs.

Not only is the radiation shield somewhat inadequate, as described above, but the radiation shield can be removed readily while the x-ray beam is ON (Fig. 5). Further, for many operations it must be removed. It is interesting to note, in fact, that many years ago the recommended alignment procedure involved a step in which the x-rays were ON while the radiation shield was off and a fluorescent disc was put in the sample position so that one might see the shadow of the anode and thereby adjust the take-off angle. Also out of yesteryear, but still in use in many laboratories, was a pole-figure device that involved flexible shafts running to a ring-like assembly put at the present sample position. This pole-figure device was too large to permit the use of the radiation shield and the flexible shafts very clearly defied any attempts to provide suitable radiation shielding, short of giving the device a room to itself.

2.3.3. Adaptations of the powder diffractometer. Since this diffractometer has been the work horse in so many laboratories, it has, of course, been festooned with a probably unimaginable variety of adapters for an equally unimaginable variety of purposes. The majority of such accessories are home-made. One such is shown in Fig. 6. This is a small furnace made of foamed silica and platinum coils wound on ceramic rods. It has been photographed in its own light generated at an operating temperature of ~ 1200°C. (Also visible are parts of the x-ray tube tower, a camera track in the foreground, and the diffractometer's beam stop attached to the counter arm in the background.) The furnace is supported by a plate of adjustable height attached to a shaft on the diffractometer axis. Since the experimenter's attention was fixed solely on getting the x-ray studies done at temperature, the design did not include any radiation shielding. As is rather typical with home-made devices, the provision of such radiation shielding is considered to be something that can be taken up after the device has been shown to perform well its principal functions. Since, by the time this demonstration is accomplished, most of the work for which the device was built is also accomplished, it is typical experience that radiation shielding for such devices never receive much conscious and directed effort. However, as is also typical of such devices, the device works very well for the purpose for which it was built, and is fairly simple and inexpensive. For our present purpose in this paper, perhaps, we should sum up this device as being a cheap, quickly made, highly effective radiation hazard!

2.3.4. Hot air furnace on single crystal diffractometer. One form of a high temperature (hot air) furnace is shown mounted on a single crystal diffractometer in Fig. 7. In order that the relationship between the direction of the hot air stream and the crystal directions does not change during the experiment, the hot air furnace moves with the crystal-mounting on the large ring. That is, when the crystal support now shown in a vertical position at the bottom of the ring is moved to a horizontal position, the hot air furnace similarly moves to a horizontal position opposing the crystal. If we may imagine, for a moment, this hot air furnace in the horizontal position and then recall that azimuthal motion of the large ring, and therefore of the furnace, is required in the process of data collection, we see that the shielding problem can be quite difficult. Further, it is also necessary that the temperature of the hot-air stream be measured as close to the crystal

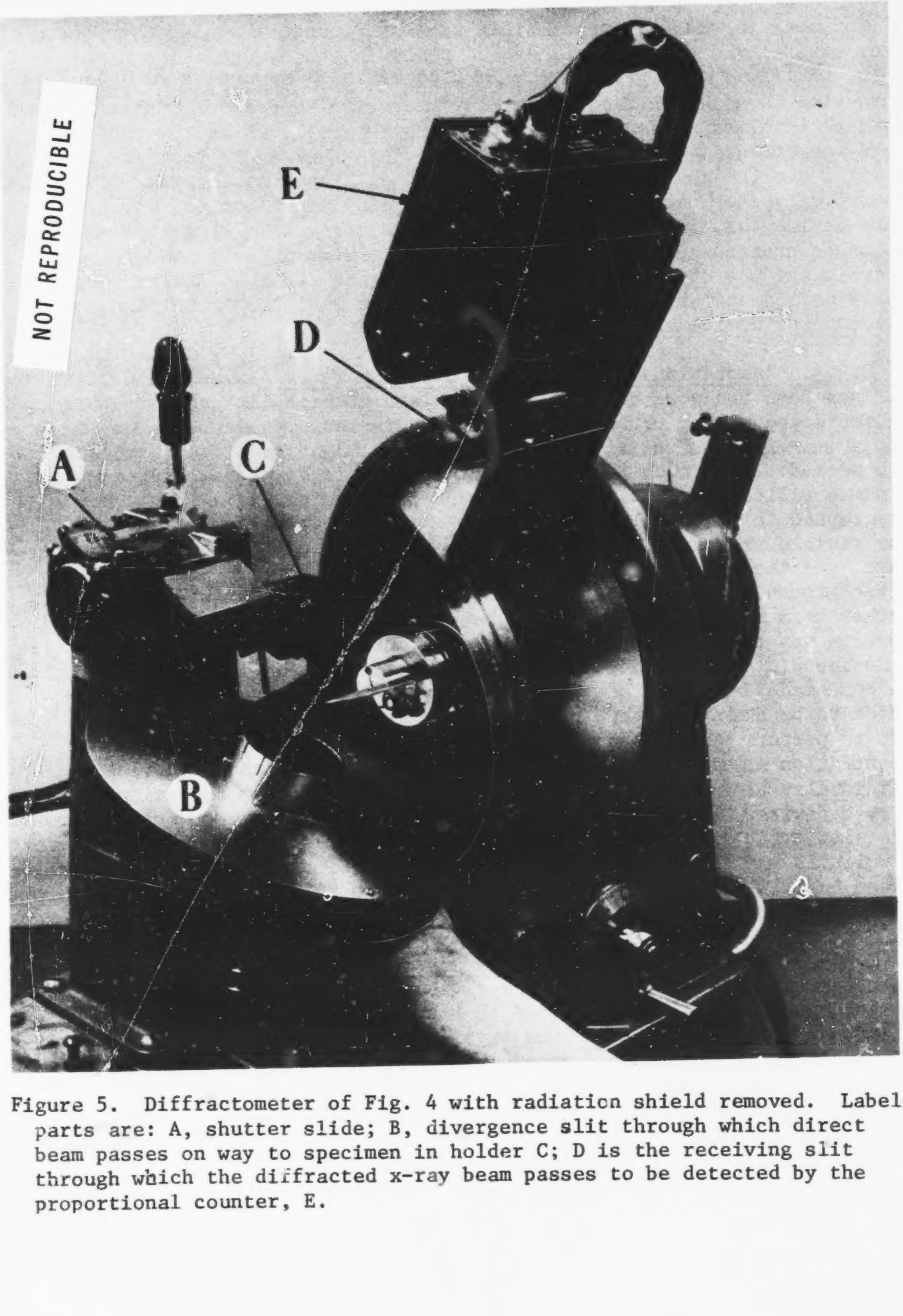

Figure 5. Diffractometer of Fig. 4 with radiation shield removed. Labeled parts are: A, shutter slide; B, divergence slit through which direct beam passes on way to specimen in holder C; D is the receiving slit through which the diffracted x-ray beam passes to be detected by the proportional counter, E.

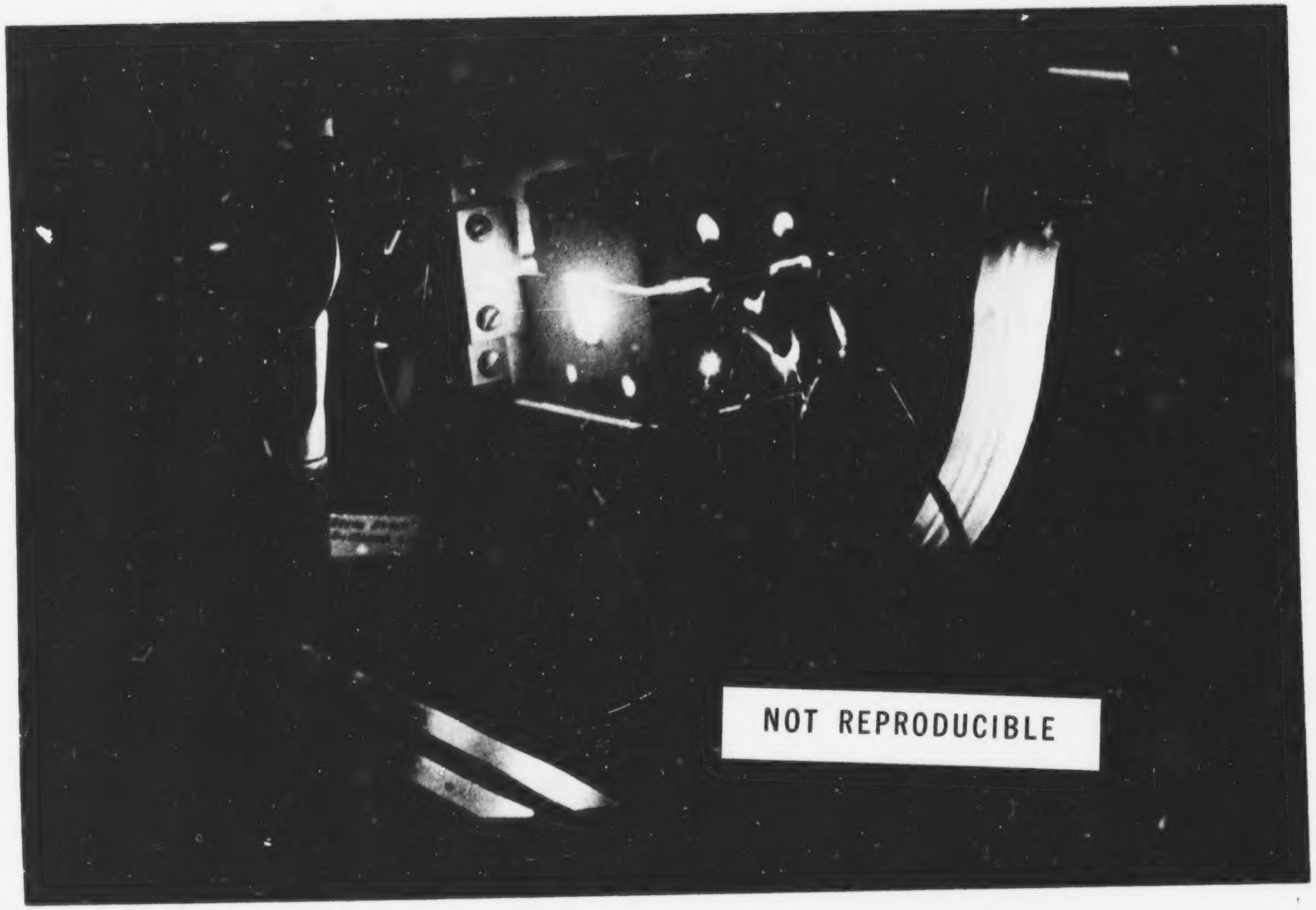

Figure 6. Special purpose specimen furnace in place on diffractometer of Fig. 4 and operating at about 1200°C.

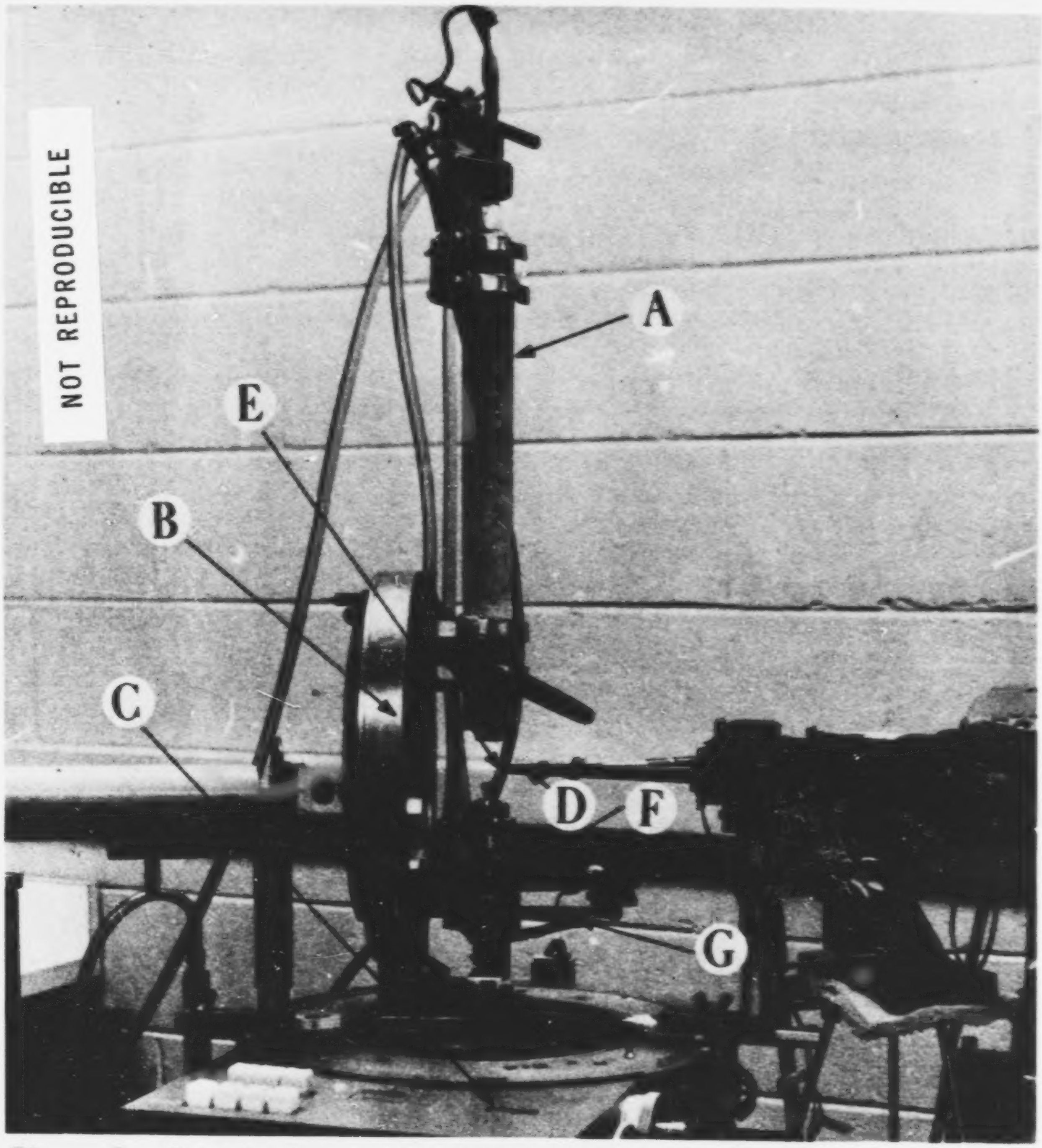

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Figure 7. Hot-air furnace A, shown mounted on "home made" goniostat B, mounted on commercial diffractometer C. Note proximity of thermocouple extending from sleeve D to small spherical specimen E held on glass fiber attached via brass plug and goniometer head to support F, which moves in vertical circle of large ring when needed. In operation, a heat shield in the form of a spherical cap of about 2 in. maximum dimension is inserted between the brass plug and goniometer head in such a way as to shield goniometer head from the hot air stream. The copper tubing G then directs a cooling air stream against the under side of the shield.

as possible. For this purpose a small thermocouple is moved with the help of a micromanipulator up to position where it nearly touches the crystal (e.g. within 0.1 mm of the crystal surface). The micromanipulator and the ceramic rod holding the thermocouple are also shown in Fig. 7.

2.4. Newer and developing x-ray diffraction techniques

2.4.1. X-ray diffraction topography. For examples of some of the radiation shielding problems that may occur with some of the newer techniques, we turn to the field of x-ray diffraction topography and related methods. A commercial x-ray topography unit is shown in Fig. 8. In this case a beam of up to 2 cm in height is used with specimens which may be two or more cm in diameter or on an edge. The incident beam is very well defined within the plane of incidence and the crystal position must be finely tuned during the process of alignment. Fig. 9 shows the slit arrangement in the diffracted beam. When the crystal is aligned the slit arrangement in the detected beam must be adjusted with x-rays ON until the slit is in the right position and just barely wide enough to pass, for example, the $K\alpha_1$ component of the diffracted beam. It is effectively impossible for one to provide a well designed beam trap for an instrument such as this; for most positions of the specimen and detector the direct beam is stopped by some part of the specimen or the slit system in the diffracted beam. It is also worth noting that the diffracted beam in this apparatus can be substantially stronger than that usually encountered in single crystal diffractometers because, relatively, much more crystal is in the diffracting position at a given time.

A topography camera made before commercial ones were available, and still in use, is shown in Fig. 10. Here attention may be called to the general openess around the specimen. This openess must be preserved in the design because both slits and films, and sometimes specimen accessory apparatus, must be free to be placed in nearly any position around the crystal. Perhaps we may label the beam stops that are used in this apparatus as "ad hoc". Such ad hoc beam stops are certainly better than nothing, but they obviously leave a great deal to be desired. On the other hand, the problem is not entirely simple, for the beam they are stopping has, or may have, dimensions of 2 or 3 cm^2 in cross section.

An additional, experimental, one-of-a-kind (i.e. "home made") topography unit and a unit for a related technique called source image distortion (SID) are shown in Fig. 11. With respect to the topography apparatus shown in the background we may note that (i) the x-ray source serves two units, (ii) for the unit fully seen the beam tunnel is very long, and (iii) the previously mentioned openess around the specimen area is evident here.

2.4.2. SID technique. The SID apparatus in the foreground of Fig. 11 is shown in a different view in Fig. 12. For the SID technique a beam that is both broad and high is used. The cross-sectional dimensions may be roughly rectangular and about one by two cm or larger. (It should be remembered that this large dimension is the dimension of the main beam in which, except for inverse square diminution, the intensity is as high at every point as it is in the small main beams used in standard single-crystal diffractometry.) Alignment of the specimen is required and is achieved by the rotation of the specimen mount on the ring shown and by turning of the specimen about the shaft

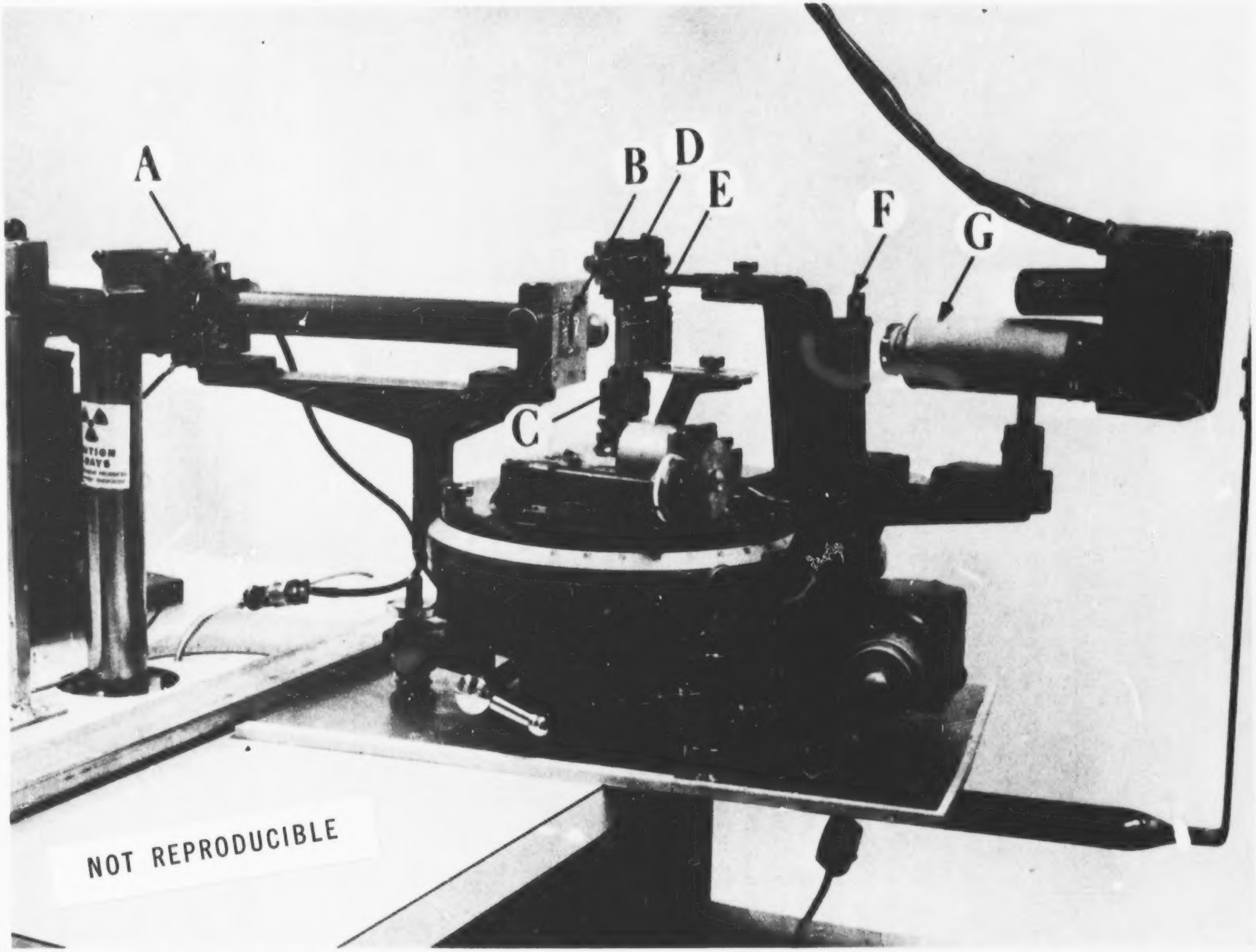

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Figure 8. Commercial x-ray diffraction topography camera. X rays generated at the microfocus source A emerge from slit B to strike specimen held (out of view) on goniometer head C. The chosen diffracted rays pass between carefully positioned long slit edges held by support D to strike film E. The alignment slit F and scintillation-counter detector G are used for alignment purposes, at which time film E and its cassette are removed and the slit edges supported by D are either removed or widely separated.

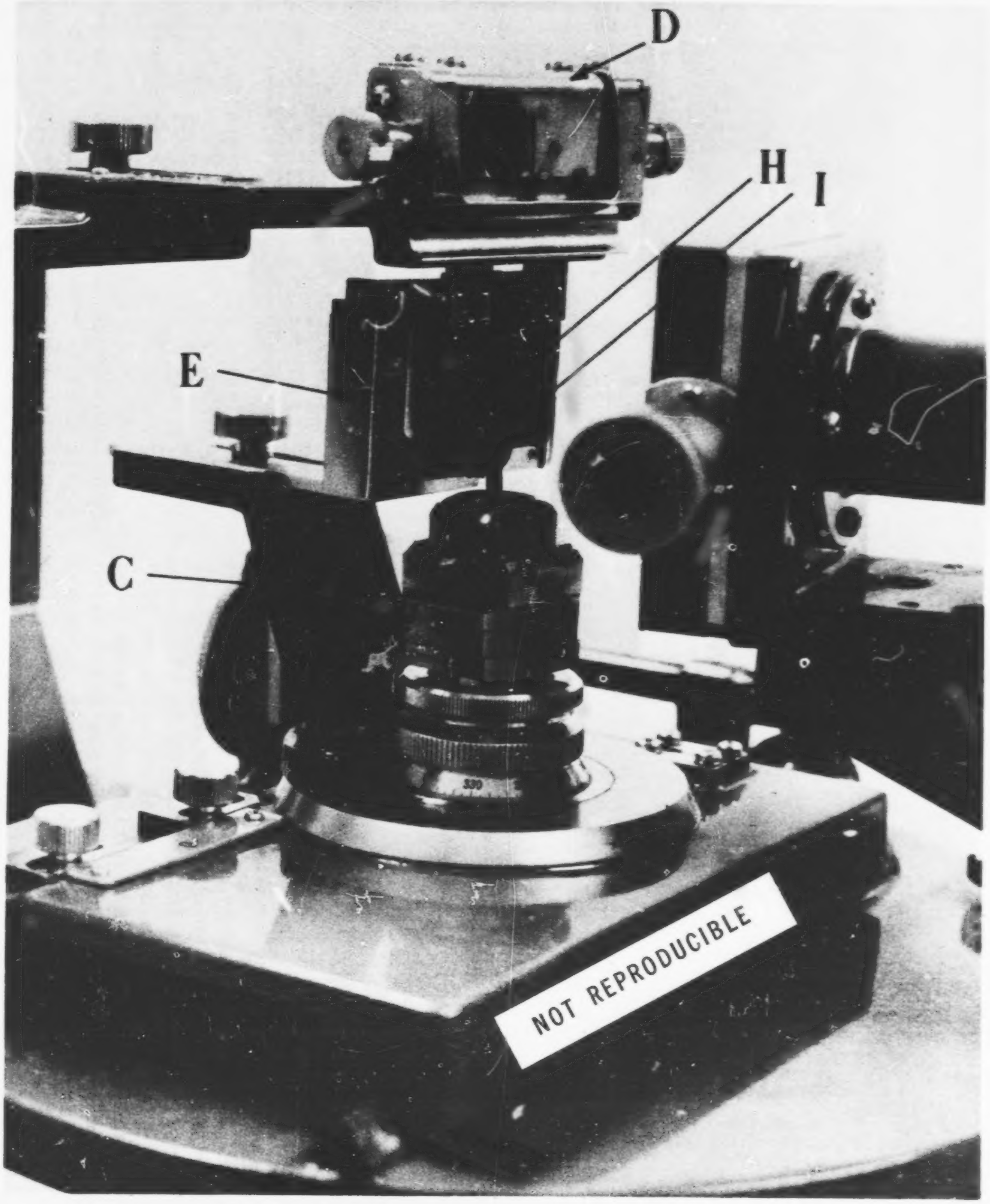

Figure 9. Further details of topography camera in Fig. 8. The labels correspond to those used in Fig. 8 with the addition of H for the slit edges supported from D and I for the specimen mounted on C.

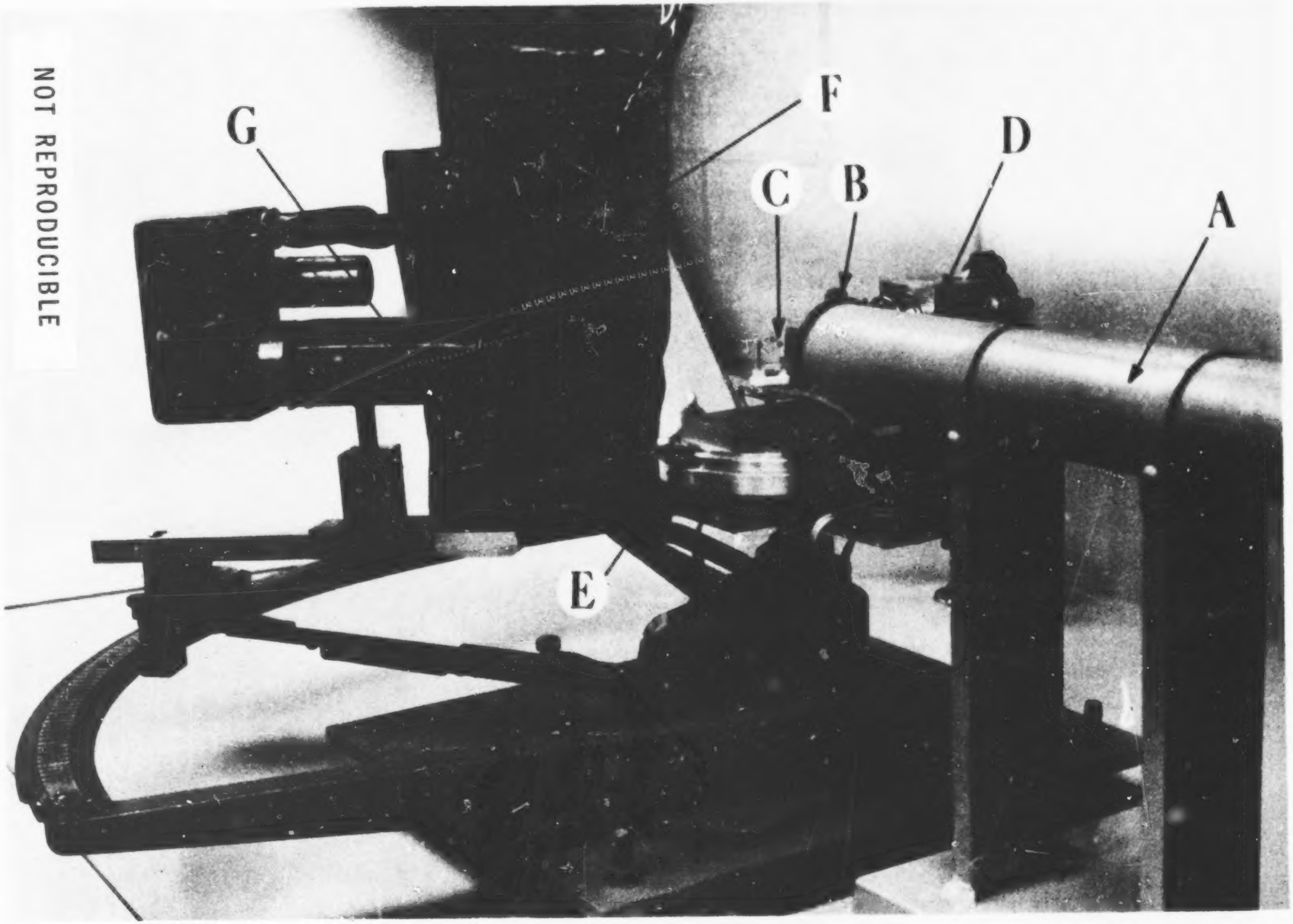

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Figure 10. Early, one-of-a-kind, x-ray diffraction topography unit. X rays from standard focus source (out of picture at the right) travel down long tube A to emerge through slit B (only top edge of slit assembly is in view) to strike specimen C which is a quartz oscillator blank mounted in operating conditon on its ceramic plug-in base. The base is mounted on a shelf supported on a horizontal goniometer head mounted on block D. Mostly out of view below block D is the synchronous-motor drive mechanism by which the entire upper assembly is caused to move slowly for 1 inch or more along ways E while the topograph is being recorded on a film (not shown) mounted on a stand directly in front of scintillation counter G, used for alignment. An ad hoc beam stop (see text) is shown at F.

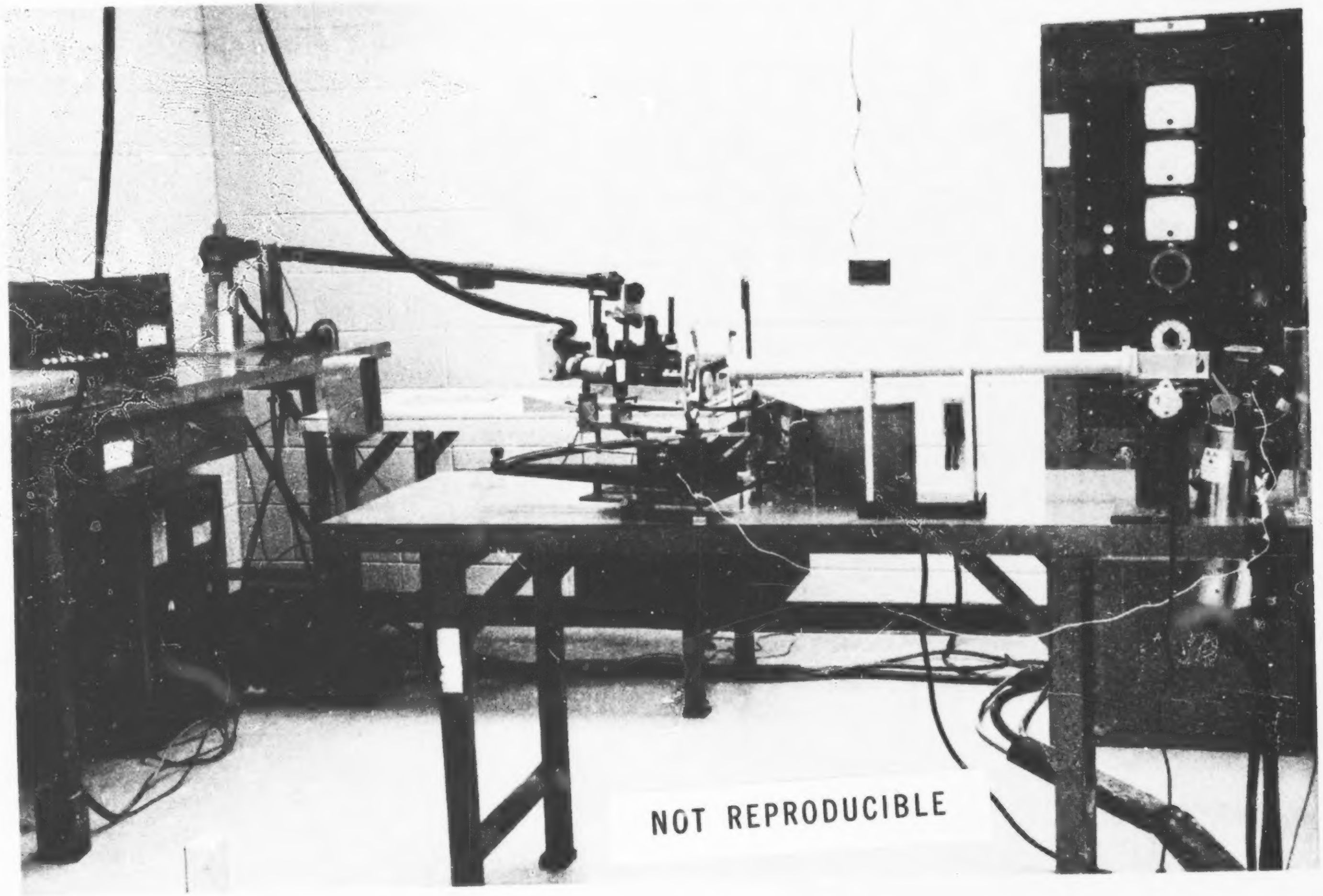

Figure 11. Two specialized units. The x-ray diffraction topography unit of Fig. 10 is shown in full in the background of this photograph. The unit in the foreground is a SLD apparatus.

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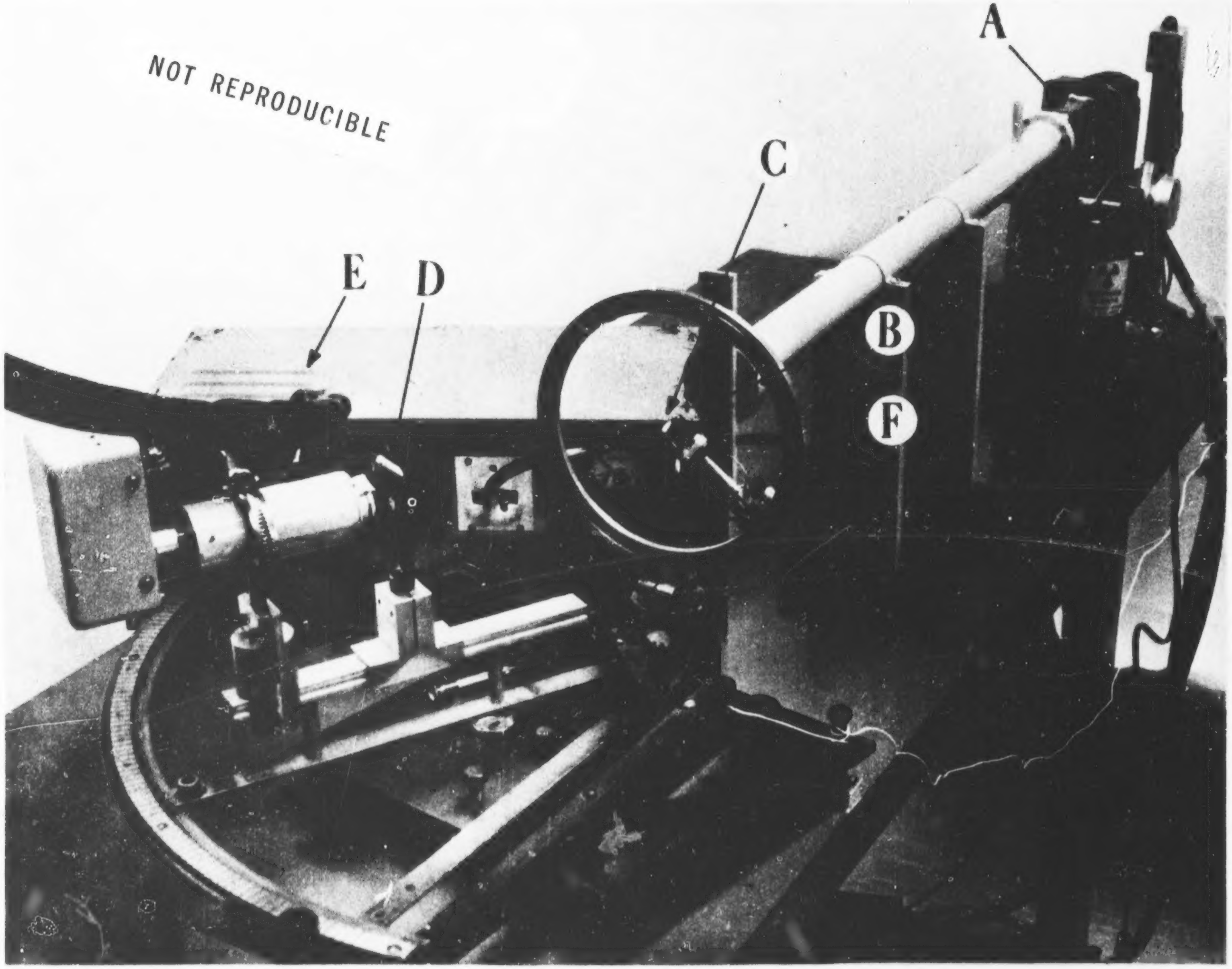

Figure 12. SID apparatus. X rays pass through a Soller slit assembly A and exit through beam-height-controlling aperture B to strike specimen C from which diffracted rays pass to (in this case) dental film in cassette D held on a simple stand. During exposure, the crystal is driven in piezoelectric oscillation by crystal impedance meter E through electrical leads F.

attached to the ring. In addition, the orientation of the plane of the ring about a vertical axis is adjustable.

The specimen itself happens to be a quartz crystal device used for frequency control. The quartz wafer with thin-film metal-electrodes and with leads attached is sealed in an evacuated glass envelope. In the case shown, the device is being examined under operating conditions, i.e. in the evacuated glass envelope with electrical signals applied. The glass envelope necessarily, being in the main beam, is a source of considerable secondary scattering. The disposition and the freedom for motion of the electrical leads must also be considered in any radiation safety device used on this apparatus.

Fig. 13 shows the collimator of this particular SID apparatus; it is simply a six-inch long assembly of Soller slits. The beam width possible is limited in this case, by the width of the window in the x-ray tube, to about 1.2 cm. A further variant of the x-ray diffraction topography technique involves the use of this SID apparatus with a reciprocating translatory motion applied to this Soller-slit collimator. In Fig. 13 the synchronous motor used for the purpose is visible. This motion, of course, complicates somewhat the radiation shielding problem. In his paper given here, Professor Samson has indicated how collimators may be attached to x-ray tubes in ways which are at once radiation safe and permit such motion.

2.5 Temptations and the principle of casual availability.

On occasion, with still larger crystals there is need in the SID technique for a beam that is higher than the present beam tunnel permits. The temptation to the operator then is simply to move the beam tunnel out of the way, as it is in Fig. 14. This illustrates what I suspect is, or what I would like to call, the principle of casual availability. For the experimenter who is intent on getting his x-ray work done, it is much easier simply to move the beam tunnel out of the way and get on with the job than it is to acquire a beam tunnel of the right diameter. The principle of casual availability is the same one which we are obeying when we use the wrong size screwdriver, or perhaps even our pocketknife, to turn a screw at the expense of damaging the slot in it as well as the tool, instead of walking across the room to pick up a screwdriver of the right size for the job. The tendency to behave in this way seems to be a major factor which must be considered in the design of radiation safety apparatus and procedures which will be acceptable and actually used by the operator. Devices and procedures, obviously, are of no value if they are so onerous as to motivate operators to subvert them rather than to use or adhere to them.

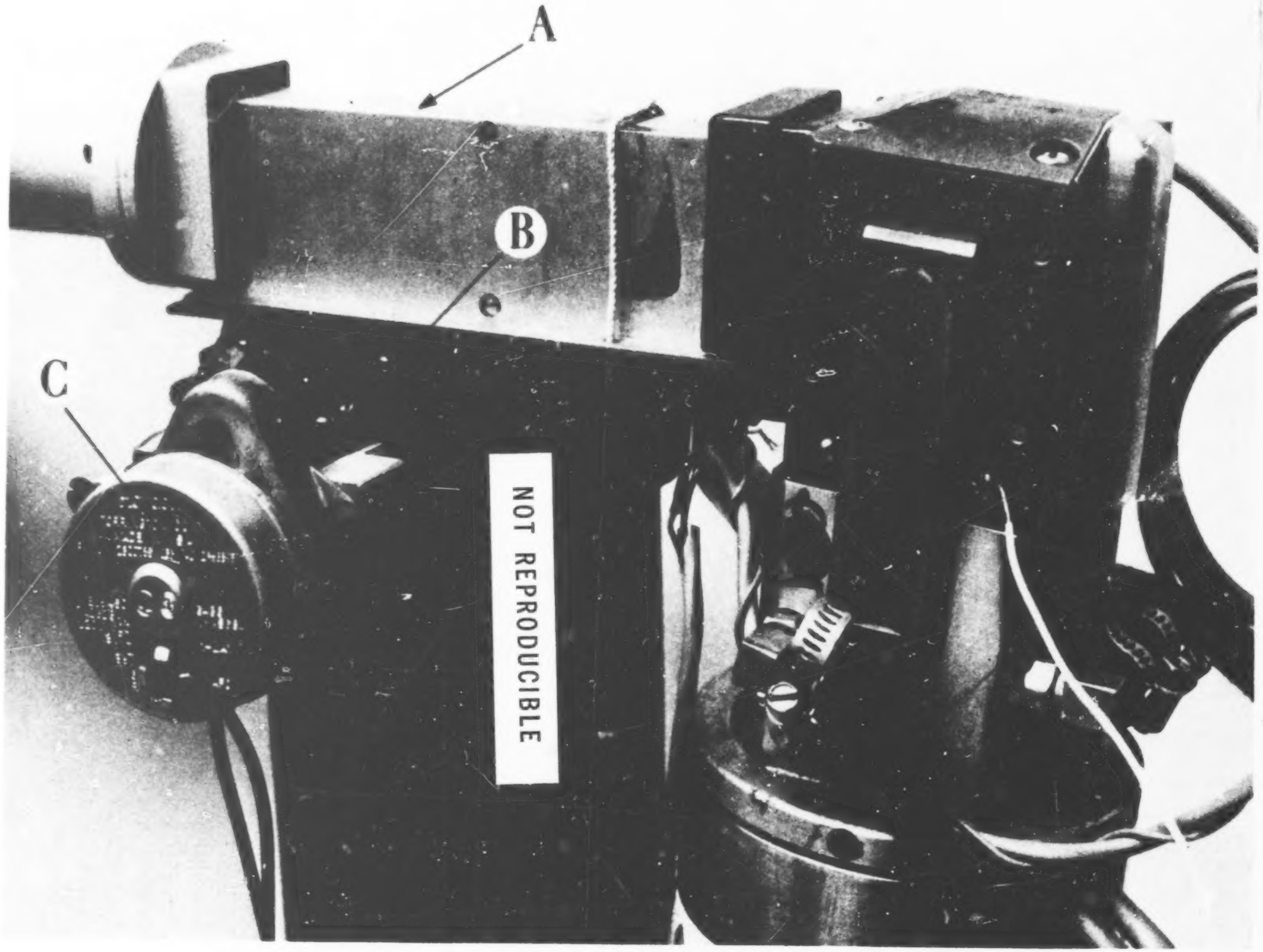

Figure 13. Soller-slit collimator assembly, A, of SID apparatus adapted for topography by provision of lateral translation of Soller slits on ways B by synchronous motor C.

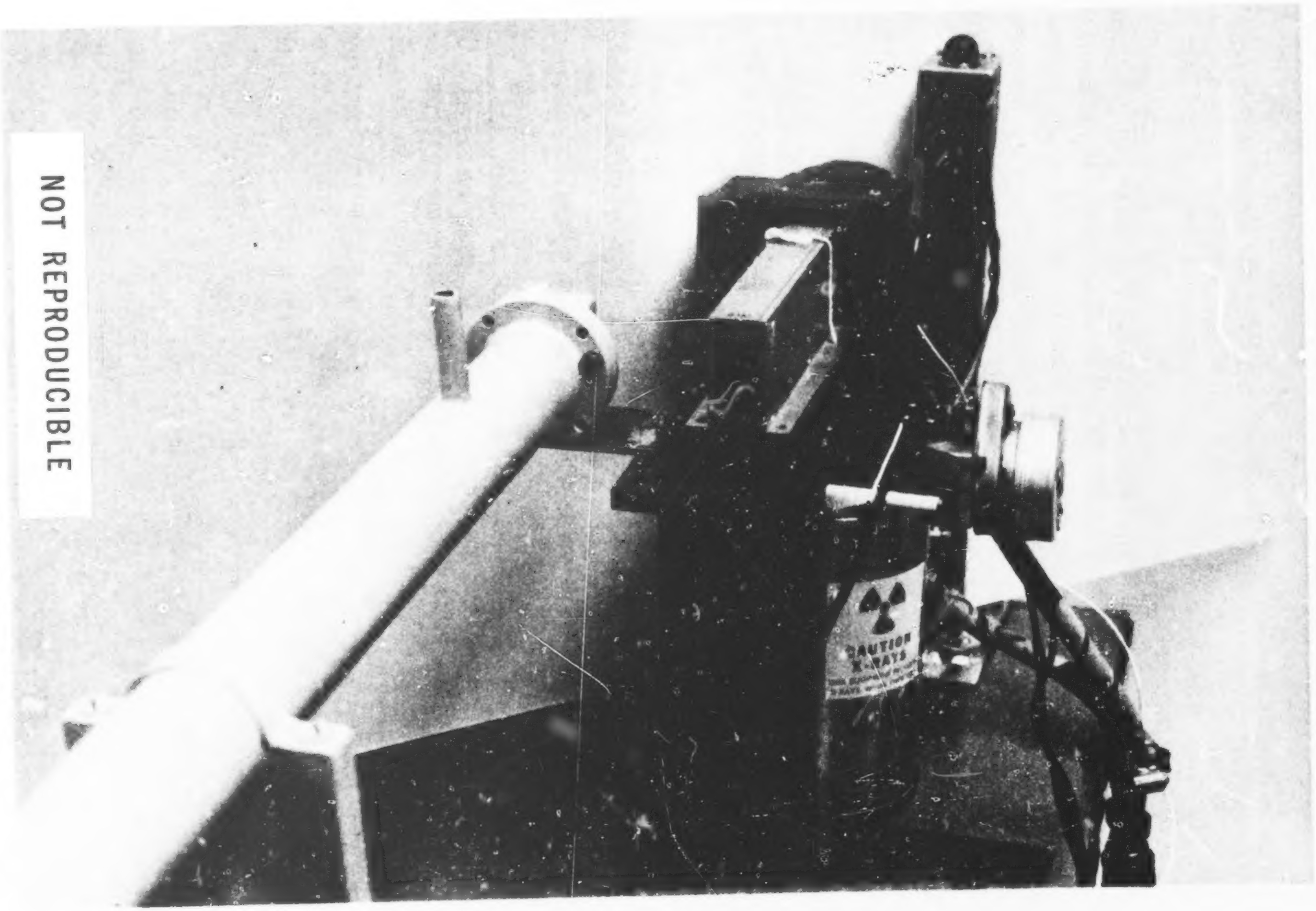

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Figure 14. Source end of SID apparatus of Figs. 12 and 13 with beam tunnel moved aside.

3. SAFEGUARDS AND THE RADIATION SAFETY PROGRAM

3.1 Reasonable goals for the Radiation Safety Program

One may, and should, ask the question of how much radiation safety should be sought. One limit would seem to be set by the recognition that the potential hazard of radiation in x-ray diffraction experiments should be treated with the respect (but not with fear). Further, in principle, we would ordinarily expect that the experimenter should be in such command of his experiment that all details are under his complete control and that, therefore, neither he nor the persons passing by will absorb so much as one x-ray photon inadvertently. The other limit would seem to be set by the aforementioned principle of casual availability; if the devices and procedures invoked to provde radiation safety are too cumbersome for him to use, the operator will either subvert the radiation safety effort or will simply not use the instrument. We certainly can all agree that both are unacceptable actions. I hope that we can all agree that we should look first to improving the methods of providing radiation safety rather than trying to control the situation through edicts imposed on the operator. (I am speaking here not of badly trained nor poorly motivated operators; I am speaking of normal human characteristics which must be considered in any viable overall solution to radiation safety.)

In our task of providing radiation safety, it is clear that a combination of hardware and procedural approaches should be used. One reason is that 100% protection provided by hardware alone would produce an inflexible, uselessly cumbersome, and therefore an unused even if not entirely unusable, apparatus. An example of such a device would be the one mentioned earlier which had the shutter interlocked with the x-rays in such a way that the x-rays were always OFF whenever the shutter was opened.

3.2 Hardware safeguards

3.2.1. Choice of examples. The possible hardware approaches may be examined in three categories, that of warning indicators, that of items interlocked with the shutter, and that of barriers against secondary (i.e. scattered) radiation. As many varieties of hardware devices can and, perhaps, will be offered as there are experimenters and configurations of the equipment. The following examples from our own laboratory are, therefore, offered only to be illustrative or usefully suggestive; they are certainly not offered as examples of approaches thought to be uniquely correct. We anticipate that we will make many changes and additions ourselves before we have developed a Radiation Safety Program which we find acceptable, even on an interim basis, by standards both of radiation safety and of acceptability to the operators.

3.2.2. Warning indicators. Warning indicators in the form of lights are illustrated in Fig. 15. Over the x-ray tube is a red light, visible from all directions of approach, which is ON whenever the high voltage applied to the x-ray tube is ON. The light is so connected that if its filament burns out the high voltage on the x-ray tube is turned off. Also showing in Fig. 15 are warning lights on each shutter. These lights, also, are interlocked such that if the filament is burned out the shutter will not open or stay open. The third type of warning indicator, not shown, consists simply of the warning signs and the familiar magenta and yellow rope used to rope off areas designated as radiation areas.

3.2.3. Interlocked devices. Items interlocked with the shutter, or x-ray source, include beam stops and beam shielding. Frequently, beam stops, particularly if placed in their most effective positions as near as possible to the specimens, must be movable so that visual alignment of the specimen, the specimen mounting, etc. may be carried out. Obviously, such beam stops should be interlocked with the shutter, or x-ray source, in such a way that if the beam stop is moved out of its normal position the shutter closes. Position-sensing microswitches and hinged beam stops are presently coming into use in our laboratories. However it is still a common method, and is our developing practice, that in addition to the movable beam stop a permanent beam stop, placed far enough away not to interfere with the alignment, be provided as a back-up safety precaution for the benefit of other persons in the room.

Professor Samson has described how collimators should be fitted to x-ray tubes. In Fig. 15 we show, with a Weissenberg camera, an example of a collimator which is electrically interlocked with the shutter. The standard collimator has been fitted with an extra brass collar, electrically insulated from the collimator itself, which must be in contact with the housing of the shutter assembly in order to complete the shutter-interlock circuit and, thus, to permit the shutter to be open. Since the first step in disassembling the Weissenberg to remove the cassette is that of moving the collimator, this particular solution seems to be effective for this particular camera.

In Fig. 16 we see a solution to the problem of mounting a Guinier camera in such a way that the freedom of motion required for alignment is maintained and, yet, the system is so interlocked that the shutter can be opened only when the camera is in place. This interlocking is accomplished by the brass washer, at point B, which is electrically insulated from the tube housing itself and is spring loaded to remain in contact with the beam tube of the Guinier camera whenever the camera is actually in place.

On the right side of the x-ray tube in Fig. 16 is shown a commercial diffractometer mounted with another manufacturer's x-ray tube and our own design of electrically operated shutter. The shutter is electrically interlocked that it can be opened only when the diffractometer entrance-opening is in proper position over a short beam tube extending from the shutter. In a later version of this diffractometer, the manufacturer has provided a mechanically interlocked shutter in the entrance tunnel to the collimator and a collimator which is fastened directly to the x-ray tube housing in a leak-proof fashion.

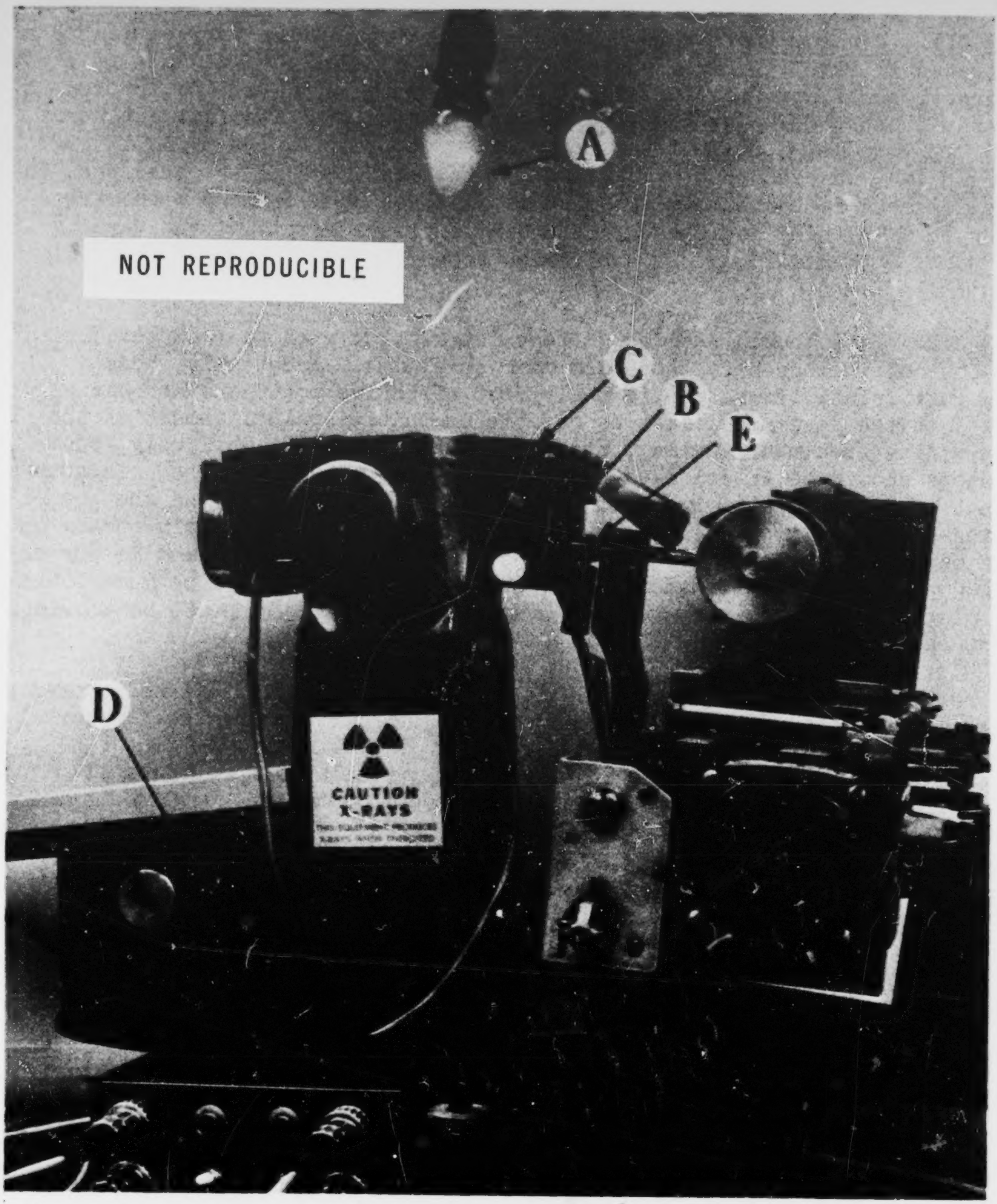

Figure 15. Indicators and interlocked devices for Weissenberg camera. Red warning light A is ON whenever the x-ray tube is energized. Red light B is ON whenever the shutter in housing C is open. The shutters are electrically controlled from box D. Collar E is electrically insulated from the Weissenberg collimator to which it is permanently fastened. Electrical contact between E and G is required to stay open.

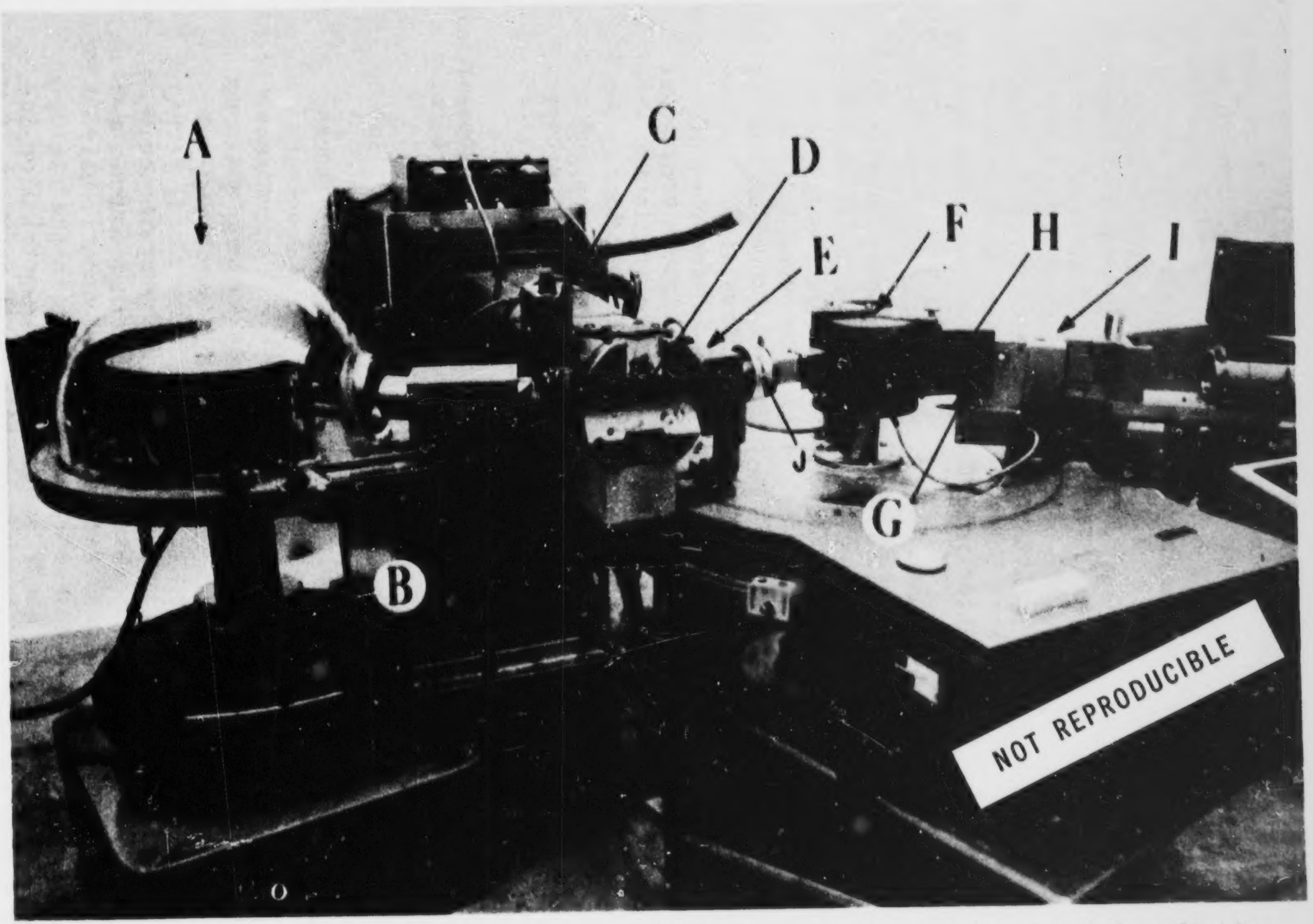

Figure 16. Guinier camera A and horizontal diffractometer in compliance with radiation safety requirements. Spring-loaded brass washer B permits camera motion for alignment while stopping back-scattered radiation when shutter C is open to x-ray source D. On the right side a microswitch interlocked with shutter E makes the shutter inoperative (closed) if collimator assembly J is not in contact with the shutter housing. The ray shield F provided by the manufacturer is hinged at I to permit access to the specimen region. When the shield is lifted, microswitch G causes the shutter to close. The heavy metal-impregnated rubberized strap H prevents the secondary scattering problem mentioned in connection with Fig. 4, region C.

3.2.4. Secondary barriers. By secondary barriers, I mean barriers against secondary or scattered radiation. It is generally felt, at least by the users, that a radiation shield completely enclosing the entire apparatus, i.e., a radiation-"proof" box or house, is not acceptable because it isolates the instrument and makes awkward or impossible the adjustments needed during the course of an experiment. Because of those facts, such a house would simply not be used and therefore would not be an effective device in practice, even though it would be if left in place. For the case of a standard diffractometer operating in a rather standard mode, a successful solution to this problem is provided by the radiation shield which is standard equipment on the commercial diffractometer shown on the right side of Fig. 16. In this case the manufacturer has provided complete shielding for the entire beam path through the diffractometer. The radiation cover at F is hinged at I. When the cover is lifted, a microswitch which we have recently added in the shutter interlock circuit causes the shutter to be inoperative in a closed position.

Another, much less complete but largely successful, secondary barrier is shown in Fig. 17. This well known commercial appartus has been modified somewhat to use a lithium flouride focusing monochromator in the incident beam. A large specimen (a metal thin film on a single crystal substrate, in this particular case) is used instead of the small single crystal for which the "goniostat" was specifically designed initially. The stainless steel "butterfly wings" shown at point A in Fig. 7 were provided by the manufacturer of the goniostat and were modified only slightly. With this equipment configuration, they are effective in protecting the operator against scattered radiation when he is in the normal working position wherein he spends most of his time. There are obviously still some weaknesses in this particular set-up with respect to beam stops and to scattering in other directions, but a large part of the required protection has been provided quite simply.

With this, we conclude our presentation of examples of the three types of hardware safeguards: warning indicators, interlocks, and secondary barriers.

3.3 Procedural safeguards

We turn now to the matter of procedural safeguards and emphasize three considerations which we accept as working hypotheses. (i) It is necessary that the procedural safeguards, as well as the hardware devices, accomodate flexibility of the equipment configuration. This is especially true while equipment repair or equipment modification, such as accompanies the working-out of a new technique or application, is in progress. (ii) In many and, perhaps, in most cases it is important that use of the equipment by non-experts be made possible. Examples of such users are students taking their first course, research students in other areas who need x-ray patterns and would be educationally benefited by collecting the patterns themselves, and beginners in the field, whether students at a university or new staff members in an industrial or institutional x-ray laboratory. (iii) A cooperative attitude on the part of the operator is a necessity and must be presupposed, for a determined man can irradiate himself, no matter what safeguards are provided.

These three points can perhaps be summed up as the need for flexibility, the need to permit use by non-experts, and the need for a conducive operator attitude.

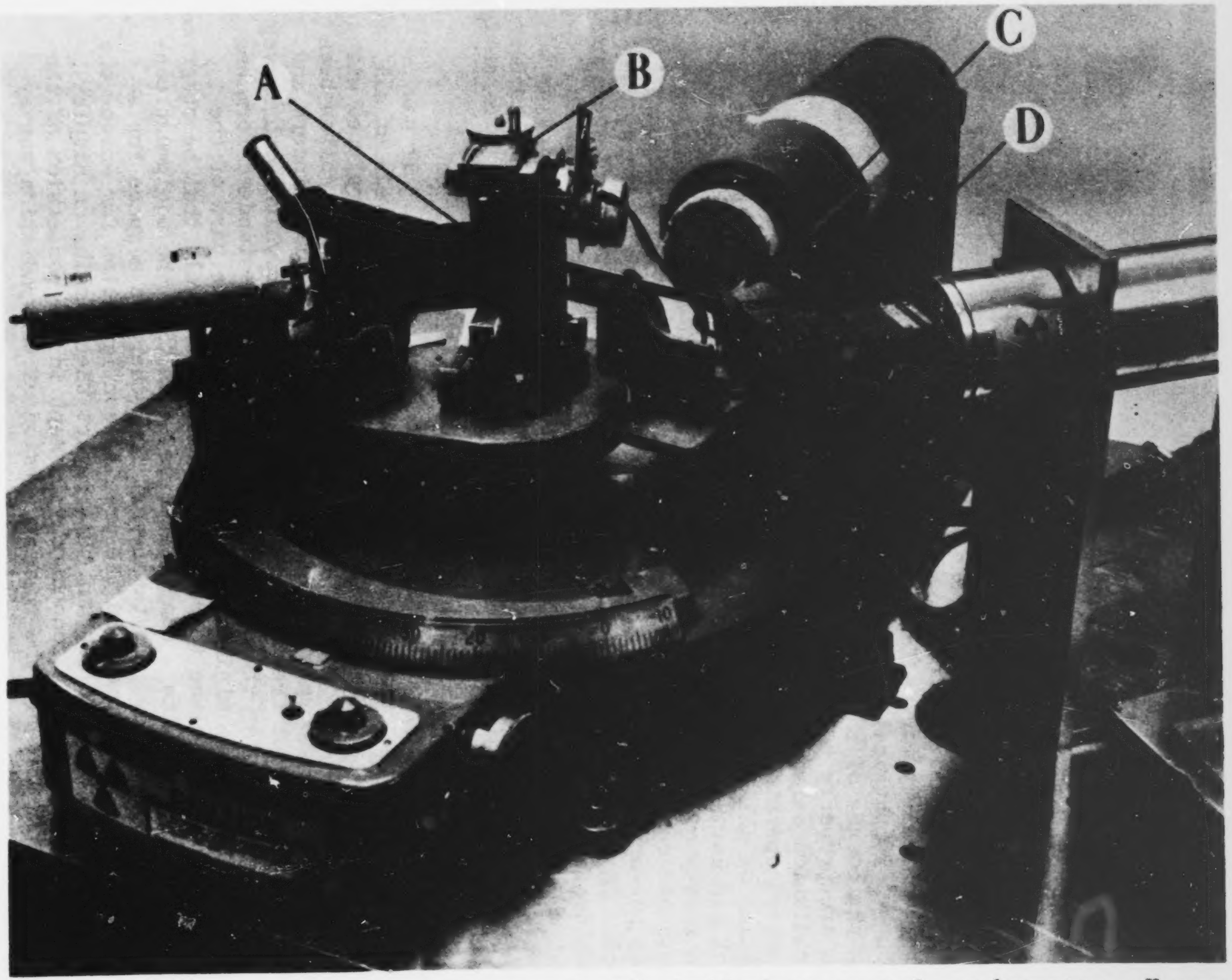

Figure 17. Commercial diffractometer used with doubly-bent crystal monchromator. X rays from source D are diffracted from cyrstal monochromator in housing C and fall on specimen mounted on goniostat B, here hidden behind the "butterfly-wings" ray shield A.

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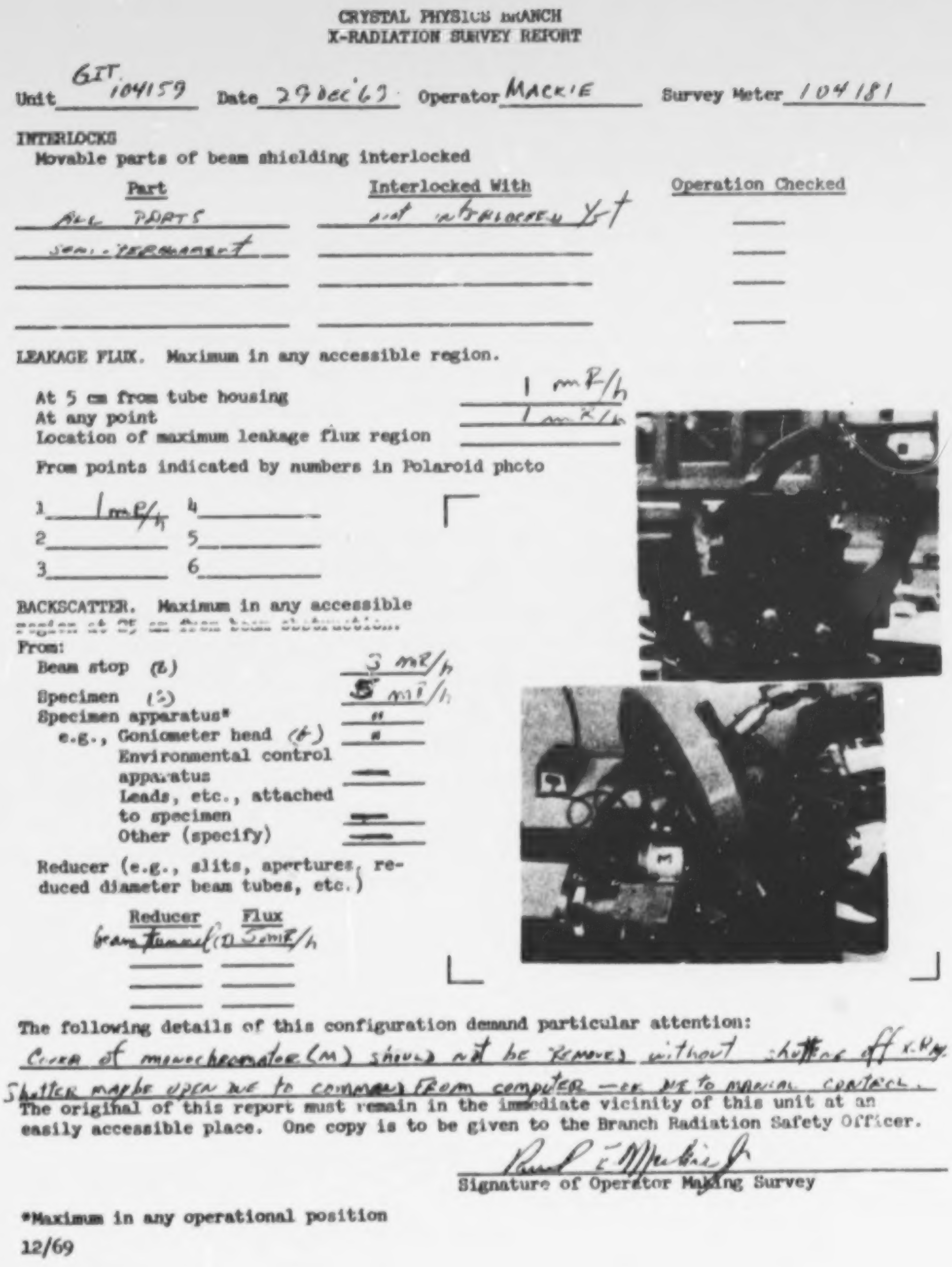
3.4 The Radiation Safety Program: one example

The Radiation Safety Program, then, will consist of some combination of hardware and procedural safeguards. No doubt a particular integration of the various elements of the program will be as varied as are the number of laboratories and their interests. However, for whatever illustrative or suggestive value it may have, we offer as an example of one possible combination of elements our present approach to a Radiation Safety Program for x-ray diffraction. There are four elements of the program, the authorized operators system, the radiation survey report, the radiation safety officers, and special monitoring procedures.

The operator is regarded as the key element in the radiation safety program. Most of the responsibility for radiation safety is placed on him because he is the one person who is physically present and able to do something about radiation safety during the course of the experiment. Authorization is extended only to those operators who are properly trained and who exhibit a cooperative attitude toward the idea of radiation safety in the laboratory. X-ray machines are turned ON only by authorized operators and the operator is then responsible for the safe use and shielding of all x-rays generated by the machine while it is operating as a result of his having turned it on. This means that he is responsible for the radiation safety of all who will work with or pass near the operating unit which he has turned on. Thus, he undertakes a specific supervisory responsibility for all use by non-experts, and for the safety of all laboratory visitors, whether or not invited. In order that they will be operated only by authorized operators, our x-ray machines have a key-operated enabling switch. So that there is no question about who is currently responsible for the operation of a particular machine, (i) the key can not be removed from the switch when it is in the enabling position and (ii) metal name tags bearing the name of the operator are permanently fastened to all keys issued to him.

The next element in the program is the radiation survey report. It has long been our policy that the operator was to know the radiation levels at all points about his instrument at all times. The laboratory has been equipped with radiation survey meters for this purpose. Undoubtedly, this rule has often been honored in the breach, not through mal-intent but through lack of reminders and a certain indefiniteness about the time and circumstances under which each survey was to be made. To make easier the observance of this rule, a standard form has been provided which requires a minimum amount of writing on the part of the operator and yet gives him a place to record the radiation levels that he observes during his survey. He is to make a complete survey each time the equipment configuration is changed in any way. On the report form there is a space for a Polaroid photograph of the equipment in the precise configuration for which the survey report has been made. One copy of this report then remains on display at the site of the apparatus and a second copy is kept in the possession of the Branch Radiation Safety Officer. The current version of the radiation survey report form is shown in Fig. 18.

Although there is a Campus Radiation Safety Officer, within our group we have appointed one of our senior professionals to be the "Branch Radiation Safety Officer". It is his task to help us check up on ourselves and to make sure that



CRYSTAL PHYSICS BRANCH
X-RADIATION SURVEY REPORT

Unit GIT 104159 Date 29 Dec '69 Operator MACKIE Survey Meter 104181

INTERLOCKS
Movable parts of beam shielding interlocked

Part	Interlocked With	Operation Checked
ALL PARTS	not interlocked yet	
semi-permanent		

LEAKAGE FLUX. Maximum in any accessible region.

At 5 cm from tube housing 1 mR/h
At any point 1 mR/h
Location of maximum leakage flux region

From points indicated by numbers in Polaroid photo

1	1 mR/h	4	
2		5	
3		6	

BACKSCATTER. Maximum in any accessible ~~region at 25 cm from beam obstruction.~~
From:

Beam stop (2)	3 mR/h
Specimen (3)	5 mR/h
Specimen apparatus*	"
e.g., Goniometer head (4)	"
Environmental control apparatus	—
Leads, etc., attached to specimen	—
Other (specify)	—

Reducer (e.g., slits, apertures, reduced diameter beam tubes, etc.)

Reducer	Flux
beam tunnel (1)	5 mR/h

The following details of this configuration demand particular attention:
Cover of monochromator (M) should not be removed without shutting off x-ray.
Shutter maybe open due to commands from computer — or due to manual control.

The original of this report must remain in the immediate vicinity of this unit at an easily accessible place. One copy is to be given to the Branch Radiation Safety Officer.

Paul E Mackie Jr
Signature of Operator Making Survey

*Maximum in any operational position
12/69

Figure 18. Radiation survey report form presently in use.

our procedures are adequate. He has the authority to suspend operation on any machine which he deems unsafe. To accomplish this, he (i) places a specially made tag, stating "Operations Suspended" and giving the date and his signature, on the machine and (ii) disables the machine by locking the main power (wall) switch in the OFF position with a special lock. He, as well as the Campus Radiation Safety Officer, spotchecks our procedures and our observation of them from time to time. In addition, he is the first person to whom any of us turn if we have any questions about radiation safety or if we need help with a monitoring procedure.

When the equipment configuration is being changed or the equipment is being modified to suit other purposes, or when a particular one-of-a-kind experiment can be carried out very simply and quickly with some normally unsafe configuration, it is often not practical nor possible for all of the normal hardware and procedural safeguards to be imposed. In such cases, it is required that the Campus Radiation Safety Officer or the Branch Radiation Safety Officer provide someone to stand by and to do 100% monitoring of the radiation levels during the course of the experiment.

In the final figure, Fig. 19, there can be seen a number of the radiation safety devices now incorporated on the automatic single crystal unit shown in Fig. 2. These include (A) a microswitch which senses whether the collimator assembly is sufficiently close to the x-ray tube, (B) a warning light on top of the x-ray tube housing which is visible from all directions of approach, (C) the deadman switch which happens to be mounted on the side of the tube mount and is needed in order to start the unit because the filament of the warning light is interlocked with the high voltage x-ray circuit, (D) unused shutters disabled by screws, and (E) on the name tag attached to the key which remains in the switch lock, the name of the authorized operator presently responsible by virtue of having turned the unit on.

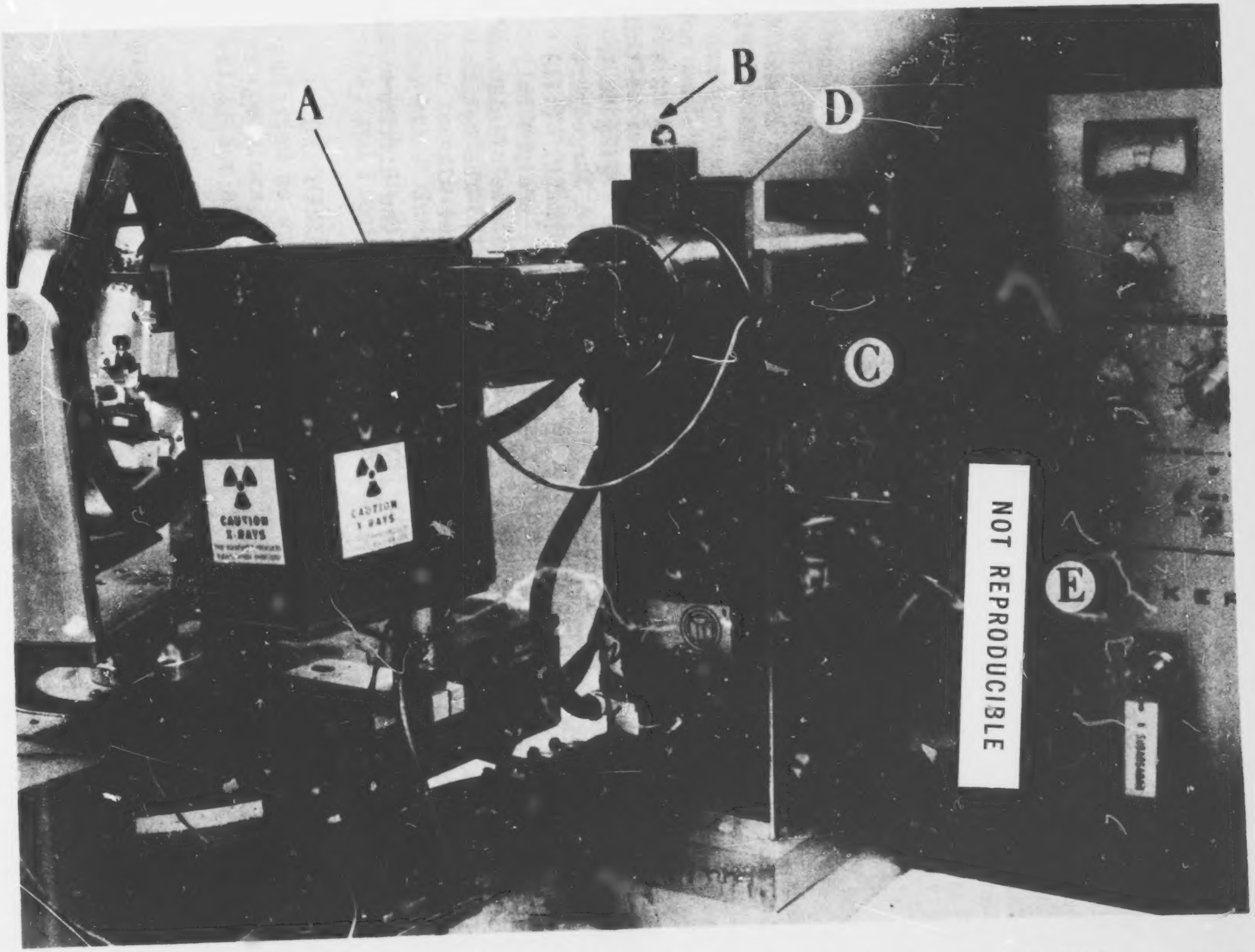


Figure 19. Radiation safety devices in use with automated single-crystal diffractometer. Labeled parts are: A - position sensing microswitch monitoring proximity of collimator to x-ray tube port; B - x rays ON warning light; C - dead-man switch required to energize initially the interlocked holding circuits; D - screw disabling unused shutter; E - key-operated power switch from which key cannot be removed in ON position. Name tag is permanently fastened to key by welded steel ring.

4. SUMMATION

Summing up, to the health physicist, I have tried to point out that the possible variety of equipment configuration is great but it is possible to have both safe and flexible operations. This will be accomplished partly through the use of hardware safeguards, partly through the use of procedural safeguards, and always with necessary ingredient of the mutual cooperation of the user and the exterior monitor, such as the health physicist. The health physicist must keep in mind the experimenter's needs for present and future flexibility and must foster the necessary spirit of cooperation by helping the user to work out mutually acceptable solutions.

To the diffractionist, I have tried to make evident: (i) Compliance with radiation safety procedures need not be too great an imposition. It is the period of readjustment that is difficult, of adjustment to a new routine but not the new routine itself. We can take heart from the experience that has been built up in neutron diffraction where radiation safety has been a design factor from the very beginning and the procedures are now not felt to be onerous by the experimenter. (ii) When it comes to working out radiation safety procedures, it is much better that we do it ourselves than have intolerable restrictions imposed on us by those who are trying to do something for our own good but do not fully understand that a large part of our "own good" is how much we can get done with the equipment. (iii) Radiation safety procedures, even seemingly stringent ones, are probably benefiting us personally. The history of the official estimate of allowable doses is a history of continually decreasing estimates. (iv) The health physicist may, just possibly, not be our natural enemy, after all!

To the manufacturers, to the health physicist, and to the diffractionist I say, therefore, lets get on with it, together.

DISCUSSION

DR. RUDMAN: I am sure there must be some points of discussion or questions.

DR. SAMSON: As far as safety procedures are concerned, I think one will have to make some distinctions between routine operations and some special types of operation that you described.

Let us say that you have a group of 20 students who are going to collect single-crystal data routinely on an automatic diffractometer. I think this puts you in a different situation in the lab, as far as the supervision is concerned, than if you have a physicist who is doing topographic studies or some sort of special investigations for which he has to modify his apparatus, and the experiment is only being performed one time and never again.

I think one should not demand -- and I agree with Dr. Young -- that one should not invest $20,000 in shielding devices and safety precautions if it is just to perform one experiment. In that case, the experimenter knows exactly what he is doing. He is aware of the dangers. He knows where to expect problems. However, for a student, a graduate student learning x-ray crystallography, we are really in a different position. We have to instruct him how to use the instrument. He has no experience at all. Furthermore, people are different, with different temperaments. Some people have their fingers in before they have their brain working; other people have the brain working before they stick their fingers in. So, therefore, one has to use different standards in different situations. This is one thing I want to emphasize, and I think Dr. Young has implicitly also emphasized it.

DR. YOUNG: Our thought is that the thesis student would become qualified as an operator. But only these people who have been qualified as operators, and who then procedurally are expected to take responsibility for all use made of the x rays they generate, will get keys.

DR. SAMSON: Yes. This key business I think is an excellent proposition.

DR. RUDMAN: Does each student have a set of keys for all instruments in the laboratory?

DR. YOUNG: Not for all instruments, because each student need not use all instruments. He has keys only for the ones that he is most likely to use.

SESSION C

RADIATION SAFETY

Moderator: John C. Villforth
Bureau of Radiological Health

RADIATION SAFETY: OBJECTIVES AND CONSIDERATIONS
John W. Thomas

THE RESPONSE OF VARIOUS SURVEY INSTRUMENTS TO LOW-ENERGY X RAYS
Ray A. Els

ROUTINE RADIATION MONITORING
Roger W. Granlund

ADVANCED DOSIMETRY AND EXPOSURE EVALUATION
Joel O. Lubenau

RADIATION SAFETY: OBJECTIVES AND CONSIDERATIONS

John W. Thomas
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The objective in radiation safety is to keep radiation exposure of man to an acceptable level without imposing undue restriction upon the use of radiation concerned. Meeting this objective may involve many considerations. This discussion will attempt to outline, from a health physics viewpoint, considerations in radiation safety in X-ray diffraction and fluorescence.

A first consideration is what constitutes an acceptable level of exposure. This is a complex matter and undergoes continuing evaluation by a variety of international and national groups. In this country, the National Council on Radiation Protection and Measurements (NCRP), a Federal charter corporation, is the principal expert advisory body. Essentially all standards concerning radiation exposure, including those of governmental regulations, reflect the NCRP recommendations concerning permissible exposure (1). These recommendations emphasize the philosophy that radiation exposures from whatever sources should be as low as practical, and set forth recommended Maximum Permissible Dose (MPD) limits. The Federal Radiation Council (FRC) of the U. S. Government, in its recommended exposure standards (2), uses the term Radiation Protection Guides (RPG). These recommended limits for acceptable exposure are essentially the same as the NCRP recommended MPD values.

Recommended MPD values are made in the light of careful consideration by experts in appropriate fields of the current knowledge of the deleterious effects of radiation. The recommended limits have been selected as representing a level of exposure which, in the light of current knowledge, could be incurred continuously with a vanishingly small likelihood of causing appreciable bodily injury to a person at any time during his lifetime. It is fully practical for most uses of radiation to be carried out with exposures substantially below the MPD, and even low levels of radiation exposure may have some potential of risk. In a good radiation safety program, the guiding principle is that exposure should be kept to a practical minimum for the use of radiation concerned.

In connection with the MPD limits, it is extremely important to remember that they are not a measure of damage or of injury. Good practice dictates that exposures should be as low as reasonably possible, but an occasional exposure of even several times the MPD is not cause for any great concern over possible injury to a person so exposed.

The maximum permissible doses for occupational exposure pertinent to X-ray diffraction and fluorescence are shown in Table 1. The unit "rem" is the special unit of dose equivalent. To define dose equivalent, several other definitions are necessary. When concerned with X or γ radiation, the roentgen (R) is defined as the special unit of exposure and is equal to that amount of X or γ radiation that produces, in one Kg of dry air, ions of one sign equaling 2.58×10^{-4} Coulombs (unit of electrical charge). Exposure rate is R per unit time. In protection, the milliroentgen, or one thousandth of a roentgen, is often the most convenient sub-unit.

By definition the R is limited to the ionization of air by X or γ radiation. A unit for the absorption of energy from a radiation field by matter is the rad. The rad is the special unit of absorbed dose and is equal to 100 ergs per gram of the absorbing material. The rad is not limited to air; it is applicable to any material including body tissues, petroleum and limburgher cheese. Nor is it limited to X or γ radiation as is the roentgen; it is applicable to any of the so-called "ionizing radiations".

The effect upon a biological system receiving a given number of rads may vary quite widely depending upon a number of factors. These include the energy and type of radiation producing the absorbed dose, the biological system itself (and also the particular effect under consideration), the rate at which the dose is received, the way the dose is distributed throughout the system and many more. The biological system of principal concern in radiation protection is the human being. For radiation protection purposes, where barring accident one is concerned with chronic, lower levels of exposure, the principal factors that may increase or decrease the risk associated with a given dose in rads are the type and energy of radiation concerned, and the distribution of absorbed dose throughout the body. To take this into account to a degree commensurate with radiation protection needs, the term Dose Equivalent (DE) is defined. The rem is the special unit of dose equivalent and is equal to the absorbed dose in rads times a quality factor, a distribution factor, and perhaps other factors in special instances. The quality factor relates to the type and energy of the radiation concerned. For fast neutrons it has been set at 10; for X-rays, one. When concerned with radiation exposure from sources outside the body, the distribution factor is reflected in the different guides specified for hands, for skin, or whole body per Table 1. The concept of dose equivalent permits MPD *values to be set forth in one unit, the rem, for α, β, and neutron radiation as* well as for X and γ rays.

The MPD values shown in Table 1 are for persons over 18 years of age, incurring exposures directly in the course of their work. Note that the annual limit for whole body exposure is actually an average over age in years past 18. For non-occupational exposure considerations, people in the general population, and for minors, lower limits are set forth. Note also, that these guides set a 13 week exposure limit and an average annual one that is less than four times the quarterly value.

Radiation control regulations concerning use of X-ray and setting limits upon occupational radiation exposure have been enacted by most states and at least one city. At the Federal level, regulations promulgated under the Walsh Healy Public Contracts Act (3), set standards applicable to X-ray exposure of personnel. AEC regulations are not primarily concerned with X-ray, but if an individual's exposure is from both X-ray and AEC controlled radiation sources, the total exposure is subject to the AEC regulatory exposure standards (4). The limits of allowable exposure set forth in these regulations are consistent with, but not identical to, the NCRP and FRC recommendations. One difference, found in a number of the regulations, is setting the 13 week limit at one fourth of the annual one (1 1/4 Rem). While possibly simpler, this is somewhat less flexible than are the NCRP and FRC recommendations.

While R, rads and rem each have special meaning, when assessing X-ray exposure situations in practice, they are often treated as equivalent. Exposure to one R of X-rays will produce an absorbed dose in tissue of about one rad and hence one rem as the quality factor is set at one for X-rays. For low energy X-rays, the absorbed dose will fall off very rapidly with depth in the exposed tissue, but even so, radiation protection surveys usually involve determining approximate exposure and evaluating the situation as if R, rads and rem were synonymous. For the large majority of situations, exposure is substantially below the recommended limits and such approximation is all that is needed, or indicated, for radiation safety purposes. It is far simpler and tends to be conservative as the actual dose will almost always be less than the exposure. Should a special situation dictate a better determination of absorbed dose, and perhaps dose distribution, it is usually done by determining the exposure in R and then from knowledge of X-ray energy, beam size, and other parameters, estimating the rad dose to the tissue of concern by calculation. An earlier paper at this conference indicated the many problems of attempting accurate dosimetry even under controlled, laboratory conditions.

Most reported injuries from diffraction X-ray have resulted from exposure of fingers or hands in the direct beam. While the direct beam in most use techniques is quite small, it is very intense--hundreds and even thousands of R per second may be involved. Obviously, even a one second exposure to the direct beam at modest distances from the X-ray tube quite probably exceeds any of the protection guide limits. More important, a single exposure of even one second duration might result in injury to the exposed region. The first evidence of injury from an excessive, single instance exposure to low energy X-rays would be a reddening of the exposed skin, an erythema. An exposure of some 300 to 400 R of low energy X-rays may be sufficient to produce erythema.

If direct beam exposure is successfully avoided, as it must be for good radiation safety performance, personnel exposure associated with diffraction and fluorescence X-ray usage should rarely need to exceed a modest fraction of the MPD. Important considerations in keeping exposures to a practicable minimum may be broken down into several general groups:

a) Equipment design

b) Equipment installation or facility design

c) Operator knowledgability

d) Radiation safety surveys and monitoring

It is in these areas that the Health Physicist and the equipment user must work in close cooperation to achieve optimum safety. Earlier presentations in this conference have demonstrated impressively that the knowledgable crystallographer and his colleagues are interested in and well informed regarding safety, and are highly knowledgable regarding safety considerations in equipment design and technique. Few, if any health physicists, have such experience and expertise in the safety considerations of equipment and its use. The health physicist's special contribution to the cooperative safety effort stems from his special capabilities in the evaluation of radiation hazards and from his primary function as a "promoter of the safe use of radiation".

Considerations in equipment design have already received excellent treatment. Some health physics oriented comments may be in order, however. Most health physicists, understandably, are advocates of safety interlocks. But, a malfunction-prone interlock or one that is not fail-safe may prove the greatest cause of a radiation hazard that could be incorporated in a piece of equipment. Interlocks should be incorporated in equipment design when, but only when, they can be designed and test proven to function reliably to minimize the risk of exposure in event of some sort of equipment failure or operator oversight. They must not be so cumbersome as to be self-defeating. When an interlock is present, even if the device has never been known to fail, its operation should be tested at reasonably frequent intervals as a normal procedure. The function of an interlock is a back-up one; to be a secondary safety feature in the event someone makes a mistake, so to speak. It should never come to be relied upon as the first line of defense.

Warning indicators are important safety features of equipment design. There should be ready indication of whether the X-ray unit is "on" or "off" and also whether beam current is "on" so that X-rays are actually being produced. There usually are several beam ports in diffraction apparatus and an indicator of the open/shut status of the shutter of each is very desirable. These indicators, be they pilot lights, mechanical, or other, should be fully evident to personnel during all normal operations about the equipment. Even the newest equipment does not always meet the desired indicator criteria; older equipment unless modified, seldom does.

As others have already stressed, a major safety consideration in equipment may arise in the interfacing of an XYZ camera system with an ABC X-ray unit. Users and equipment manufacturers should benefit greatly by on-going efforts in the voluntary standardization of some aspects of shutters, coupling systems and other apparatus.

In many applications of radiation, safety aspects of equipment installation and facility design are of primary importance. The emphasis properly may be less with respect to X-ray diffraction and fluorescence, but it is important not to overlook these considerations. Special, structural shielding is rarely necessary for X-ray equipment of this nature. Some equipment is, or can be, designed or modified so that it is completely enclosed during all normal use. Where this is not feasible, much shielding still is accomplished most effectively by proper beam traps, coupling systems, camera design and by use of small shields positioned locally for best results. Where a wall or partition may be a part of shielding, most typical wall constructions provide ample shielding for the low energy X-rays concerned. Very light construction, a decorator panel of fiber glass or thin masonite on open studs could be exceptions, but walls having the mass equivalent of two thicknesses of heavy plaster, or two pieces of 5/8" thick plaster board, will meet almost any shielding needs for diffraction installations.

In practice, equipment location and orientation is more frequently of importance than is structural shielding. Equipment is often found in multi-purpose labs, in space also serving as office space; there may be several units located in one lab area; or a unit may be located in a high traffic area. Such situations can present numerous problems. If there is a high occupancy time of areas close by the X-ray equipment, allowable radiation levels must be determined on the basis of long exposure times rather than for the relatively short periods required for operational set-up and adjustments. With multiple unit installations, the additive exposure resulting from all units must be considered. Equipment in a high traffic area may increase the number of persons who may be exposed -- including some whose occupation shouldn't involve radiation exposure in the first place. Such locations also enhance the risk of tampering or accidentally disturbing the equipment set-up and operation. Equipment should be located in a room or area where access is controlled and where occupancy is limited to that necessary for the use of the equipment. Orientation of equipment within a room may be important, particularly where several units are together in one area. Often, one beam port will be used preferentially for operations involving greater levels of what may best be called stray radiation and a definite asymmetry exists in the radiation levels about the equipment. If equipment is properly oriented, the regions of higher exposure will be chosen so that they are the low to no occupancy parts of the room. This can often reduce the need for special precautions.

Equipment and facilities are important, but the people using the equipment are more important in good safety performance. A major consideration is to see that operating personnel are instructed in the use of the equipment, the hazards associated with their use of the equipment and the safety procedures to be followed. Even the least sophisticated operators should be fully aware that they are using radiation producing equipment, should know the proper techniques for the work that they perform, should be familiarized with the symptoms of a recognizable injury and should know to whom to report suspected accidents or equipment malfunction. Good radiation safety practice will give special attention to orientation and instruction of personnel.

Some of the complicating factors in radiation safety are the inability of the human senses to detect the presence of radiation, the possible long delay between exposure and deleterious effect or injury, and that effects may result from cumulative exposures. Thus, radiation safety places special emphasis upon radiation surveys and monitoring. The terms are often used synonomously, but in the strict sense, surveys refer to evaluations made under specified conditions and monitoring applies to a continuing, "watch dog" process such as personnel monitoring. Surveying and monitoring instruments and their use will be treated in more detail in later presentations, but a few comments will be made here.

The usual survey meter used for X-rays in radiation protection consists of a radiation detector such as a Geiger-Mueller Tube, a scintillation detector, or an ion chamber, together with portable electronics and a meter read-out. The instruments may be quite energy dependent, particularly for low energy X-rays. Where small beams are involved, response will depend on the fraction of the sensitive volume of the detector actually intercepting the beam, and small beams may easily be missed completely if considerable care is not exercised in use of the instrument. Further, the instruments may be rate dependent; they may saturate or even fail to respond at all if exposed to very high exposure rates.

But, this does not mean that survey meters are not of great value in X-ray diffraction or fluorescence labs or that they should only be used by highly qualified and experienced personnel. Any of several types of survey meters are valuable in day-to-day operations. They may be, and should be, used by laboratory personnel as screening devices to confirm the absence of excessive radiation levels, or to locate a deficiency in shielding or a coupling system which should be corrected. A large majority of survey/monitoring needs are met by just this sort of screening process. But, when more than such a screening survey is indicated, expert advice should be sought, for the measurement of and evaluation of radiation hazards from low energy X-rays may be complex, even for health physicists.

Personnel monitoring is an important procedure in radiation safety. The monitored individual wears a film badge or analogous device to monitor the radiation environment through which he moves in the course of his work. In almost all personnel monitoring techniques, the information derived from the monitoring device is retrospective; it provides an indicator of the monitored individual's possible exposure after-the-fact. The information provided is of value as either confirmation of satisfactory safety performance, as a warning of possible lapses in safety practice, or of an otherwise unsuspected excessive exposure. In X-ray diffraction and fluorescence, personnel monitoring is far less informative than in many other areas of radiation usage. Film badges are definitely energy dependent at lower X-ray energies. Thermoluminescent dosimeters may reduce the energy dependence, but the actual accuracy of the monitoring device is but a small aspect of the problem. The monitoring device is physically small and even if one is worn on the chest, another on the hand, and yet another on the forehead, nearby body regions might incur significant exposure without the monitoring devices giving any indication. Nor does a positive result give any great assistance in assessing the extent or degree of exposure to the monitored individual. Still, personnel monitoring is of some value, for if positive results are investigated, it may aid in finding and correcting deficiencies before an actual injury or excessive exposure occurs. Personnel monitoring is desirable, but its very considerable limitations must be recognized.

The forgoing discussion has attempted to indicate the scope of considerations involved in radiation safety in X-ray diffraction and fluorescence. A number of factors are involved, some simple and some complex, and the overall needs in radiation safety will be greatly dependent upon the nature and extent of the uses of X-ray concerned. The last consideration to be discussed here is perhaps the most important of all. There must be a clearly established, planned radiation safety program. In a limited use situation, this may be established at the laboratory level; in a large complex, the laboratory program may be a part of an organization-wide one. The program should be a clearly established policy, made knownto all concerned. Someone must be in charge of the program. The program and procedures implementing the program should be developed by qualified personnel which may indicate use of consultants to supplement expertise available within the concerned organization. The establishment of a program is basic; it means that radiation safety has been recognized as too important to be left to chance.

TABLE I

MAXIMUM PERMISSIBLE DOSE EQUIVALENT (MPD) FOR EXTERNAL EXPOSURE
(Partial Listing)

Type of Exposure	Maximum 13 Week Dose	Maximum Yearly Dose	Maximum Annual Dose
Radiation Workers:			
Whole body, gonads, active blood forming organs, lens of eye	3 rems	-	5 (N-18) rems
Skin of whole body	10 rems	30 rems	-
Hands and forearms	25 rems	75 rems	-

Notes: N = Age in years and is greater than 18

Exposure of patients for medical and dental purposes not included in MPD.

ADDENDUM

In January 1971, the NCRP issued revised recommendations (Report #39, see Ref. 1). The new NCRP recommendations differ from the above in several ways. Actual reductions from above values are as follows:

Skin	15 rems in any one year
Forearms	30 rems in any one year (10/qtr.)

REFERENCES

1) National Committee on Radiation Protection and Measurements, "Permissible Dose from External Sources of Ionizing Radiation", NCRP Report No. 17 (1954) (Including addendum issued on April 15, 1958)

NOTE: The above NCRP report has been superseded by the following:

National Council on Radiation Protection and Measurements, "Basic Radiation Protection Criteria", NCRP Report No. 39 (January 15, 1971). (Available at $2.00 from NCRP Publications, P. O. Box 4867, Washington, D.C. 20008)

2) Federal Radiation Council, "Background Material for the Development of Radiation Protection Standards", FRC Report No. 1, 1960. (Available from Superintendent of Documents, U. S. Government Printing Office, Washington, D.C.)

3) Code of Federal Regulations, Title 41, Chapter 50, Part 50-204, "Safety and Health Standards for Federal Supply Contracts", Subpart C, "Radiation Standards".

4) Code of Federal Regulations, Title 10, Chapter 1, Part 20, "Standards for Protection Against Radiation".

THE RESPONSE OF VARIOUS SURVEY INSTRUMENTS TO LOW ENERGY X RAYS

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ABSTRACT

Several commercially available survey meters were exposed to low energy, fluorescence x rays to evaluate their usefulness as low energy x-ray survey meters. The systems tested in this study were: a Victoreen 440, a Victoreen 440 RF, a Victoreen 444, an Eberline E500B with an end-window G-M tube, and a Victoreen 1B85 G-M tube in a scaler-timer circuit.

Common survey instruments are usually calibrated using gamma radiation with a photon energy on the order of 1 MeV from a radioactive source. The instruments tested here were exposed to gamma rays from a calibrated cesium-137 source. Their responses were within manufacturers' specifications for calibration accuracy.

They were then exposed to the characteristic K-fluorescence x rays of copper and molybdenum, 8.05 keV and 17.48 keV respectively.

It was found that the Victoreen 440, Victoreen 440 RF, Victoreen 444, and Victoreen 1B85 exhibited response characteristics useful for routine radiation surveys when exposed to the molybdenum fluorescence. None of the instruments exhibited as useful a response when exposed to the copper fluorescence.

INTRODUCTION

In the laboratory and in the field one is often faced with the problem of determining the exposure rate of radiation emitted to the environs by radioactive materials or electronic radiation producing sources. A detailed determination of the exposure rate in such cases is usually not required, since one is usually willing to sacrifice some degree of accuracy in measurement for speed in obtaining an exposure rate reading if a health hazard is suspected. This is an important consideration in the selection of a radiation survey instrument appropriate to the situation.

Having decided on the use of a particular survey instrument, it is then desirable to know just what accuracy may be expected in the situation at hand. One should be aware of any large errors associated with use of a survey instrument especially if it reads significantly lower than the actual exposure rate. The manufacturer of a survey instrument usually makes available to the purchaser information concerning the energy dependence and accuracy of the meter. The purpose of this study is to supplement such information, for the special case of low energy x rays.

It has become increasingly important to be able to measure the exposure rate due to low energy x rays since considerable scientific and industrial work is performed utilizing products that have the capability of emitting x rays in this energy region. This study will ascertain the response of several of the widely used survey instruments when exposed to known fields of low energy x rays.

EXPERIMENTAL

The exposure readings were determined with the instruments exposed to a uniform x-ray beam of essentially monoenergetic composition. Exposure rates were determined using an intercomparison standard ion chamber with calibration traceable to the National Bureau of Standards. Such ideal conditions are rarely present during the normal usage or conventional calibration of survey instruments. Usually the x-ray field will be nonuniform with an unknown exposure rate and a spectrum of energies. In order to understand the operating characteristics of an instrument it is desirable to investigate its response under well defined conditions. This fundamental knowledge can then be expanded to simulate responses to the conditions usually encountered.

X-ray Energies. For the purposes of this experiment it was desirable to have as nearly monoenergetic an x-ray beam as possible. The x rays used were the characteristic x rays from copper and molybdenum radiators, excited by an x-ray beam generated with a Westinghouse Coronado 250 kV unit, see figure 1. With one of the above radiators placed in the "primary" beam at a 45° angle, a secondary beam composed principally of the characteristic x rays of the radiator was available at the exit port of the apparatus. There is an insignificant amount of bremsstrahlung present in the secondary beam because x rays are used for excitation, not electrons. Both the primary and the secondary beam were collimated using brass and lead shielding in order to provide a secondary beam with a low content of scattered x rays.

The energy distribution function, N(E)dE, is the number of x-ray photons per unit area per unit time in the energy interval dE centered at a given energy E. Once this function has been experimentally determined, one can make calculations to indicate the quality of the x-ray beam. In this case the more nearly monoenergetic the beam, the more suitable it is for our purpose.

There are two general approaches used to determine the energy distribution function for x rays: the dispersive and the nondispersive approach. With the dispersive approach a well collimated x-ray beam is passed through a diffraction crystal and the spatial distribution of the diffracted beam is monitored using various detector techniques.

NOT REPRODUCIBLE

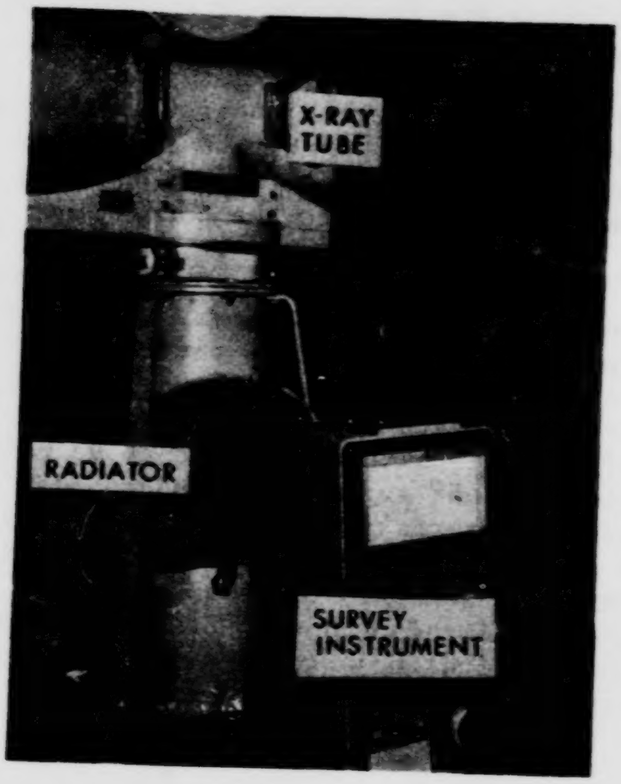

FIGURE I. GEOMETRY FOR EXPOSURE OF SURVEY INSTRUMENTS

The x-ray beam is diffracted according to Bragg's Law, which can be written in the form

$$\theta = \sin^{-1} (\lambda/2d) \tag{1}$$

where λ is the wavelength of the x-ray photon, d is the spacing of parallel lattice planes in the diffraction crystal, and θ is the angle of diffraction. As one can see, the more energetic the x-ray beam the less it will be dispersed by the crystal. This approach yields better energy resolution than the nondispersive technique but must be corrected for detector sensitivity and crystal transmission. The overall sensitivity is poor due to the low efficiency of the dispersion of the x-ray beam in the crystal.

The approach used in this study to determine the x-ray energy distribution functions was the nondispersive pulse-height analysis of charge pulses consisting of electron-hole pairs created in the intrinsic region of a semiconductor diode primarily by photoelectric interaction of single photons with the material. The x-ray beam impinged upon a lithium drifted silicon detector. The detector produces electrical pulses with amplitudes proportional to the energy of the x-ray photons. The pulses were then sorted according to amplitude by a 1024 channel pulse-height analyzer. The advantages of the nondispersive method are: (1) for photons with energy less than 30 keV a Si(Li) detector with a thickness of 3-5 mm is nearly 100% efficient, (2) a low photon flux can be detected with relative ease, and (3) data gathered using this technique lends itself more easily to computer analysis.

The energy spectra for the copper and the molybdenum radiators are shown in figures 2 and 3 respectively. Each spectrum has principal peaks at two energies, the lowest energy peak being an unresolved doublet composed of $K\alpha_1$ and $K\alpha_2$ x rays and the highest energy peak an unresolved $K\beta_1$ and K_{β_2} doublet. These figures are the pulse-height distributions, uncorrected for detector efficiency, resolution, scattering or escape effects.

A calculation was performed to ascertain what percentage of the secondary beam flux was due to K-fluorescence x rays (either $K_{\alpha_{1,2}}$ or $K_{\beta_{1,2}}$), and it was found that approximately 90% of the total flux from either radiator was in this energy region. The remaining flux (10% of the total) was probably due principally to coherent scattering of the primary beam by the radiators. The majority of these scattered x rays have energies above the characteristic x-ray region, the reduction in scatter could probably have been affected by lowering the operating potential of the x-ray tube while keeping it above the excitation energies of copper and molybdenum. The lowest potential available with the x-ray unit used was 30 kVp which is about 10 kV above the excitation energy of molybdenum and more than 20 kV above that of copper.

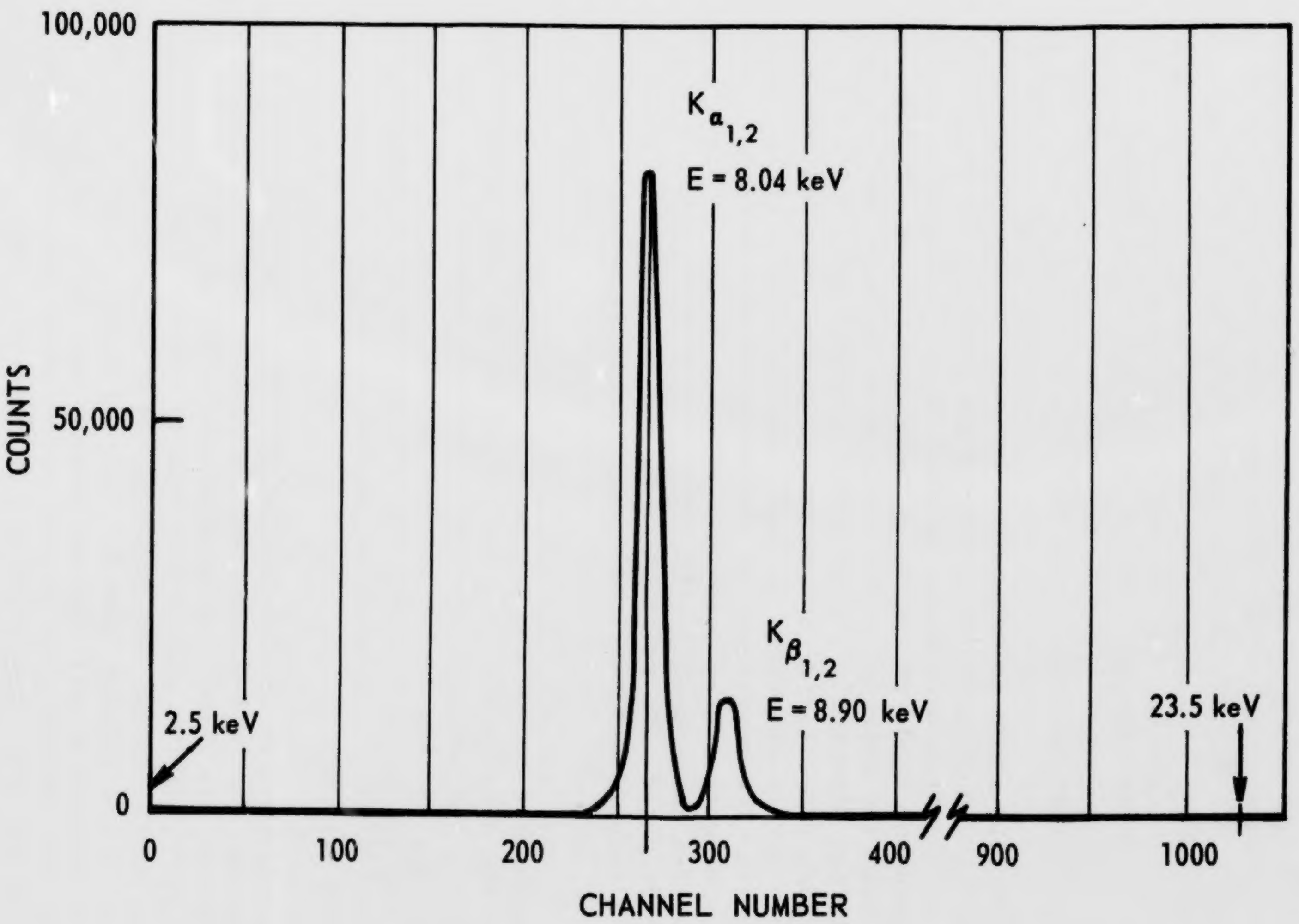

FIGURE 2 : ENERGY SPECTRUM FOR COPPER RADIATOR

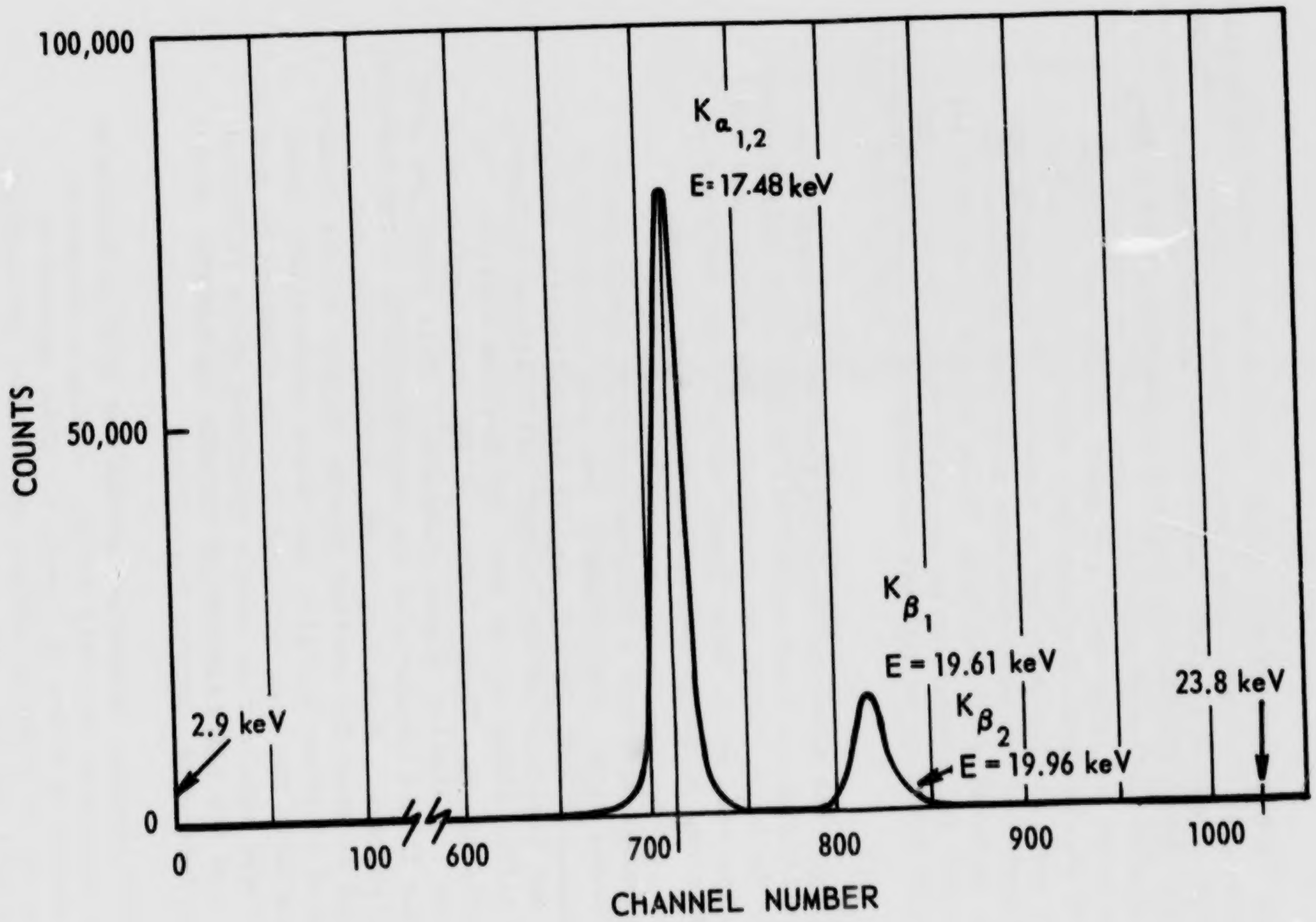

FIGURE 3 : ENERGY SPECTRUM FOR MOLYBDENUM RADIATOR

Henceforth, for convenience, the $K_{\alpha 1}$ x-ray energy will be taken as the effective energy of the beam for the radiator. For copper and molybdenum radiators these energies are 8.05 keV and 17.48 keV respectively[1].

Beam Uniformity. A majority of the survey instruments tested employ ionization chambers as the detection element. These chambers are of large volume when compared to G-M tubes and have window diameters of up to nine centimeters. To achieve a true response for a given exposure rate from these large chambers, they must be exposed to a beam that is at least as large as the chamber window and uniform over the area of the window. The exit port for the characteristic x-ray generator used in this work had a diameter of nearly fifteen centimeters, therefore, the beam size was more than adequate. To investigate the uniformity of the beam, Kodak Type M x-ray film was exposed at the port and scanned using an Ansco Model 12A densitometer. The x-ray beam was found to be uniform to within ± 3% over the area of interest.

Beam Exposure Rate. The absolute exposure rate of the x-ray beam was determined utilizing an intercomparison chamber with calibration traceable to the National Bureau of Standards. The system used was similar to one discussed by E. Dale Trout, et al[2], and included an ionization chamber and a charge collection measuring system.

The ionization chamber used was a thin-walled (0.01 inch) cavity chamber of the Shonka type. This chamber had been calibrated at three energy points, 21 keV, 25 keV, and 28 keV (effective energy), by NBS. It was not possible to obtain NBS' calibrations at lower energies due to difficulties at the NBS' calibration service. In private communications, Mr. Thomas Loftus of NBS made mention of a study performed on six similar Shonka chambers[3]. This study included calibration of the Shonka chambers at the characteristic x-ray energies of copper and molybdenum. According to Mr. Loftus, these two calibrations could be used for another Shonka chamber if the chamber had been calibrated at other energies and these calibrations found to be in agreement with the ones obtained for the chambers he used in his study. The three calibration points mentioned above fulfilled this requirement and the NBS calibration for the six similar Shonka chambers was therefore used.

A charge collection exposure measuring system was used to determine the standard exposure rates for this study. A simple schematic diagram of this system is shown in figure 4. When exposed to radiation, ionization is produced within the chamber and current flows between the wall and the collector electrode of the chamber under the influence of the chamber bias voltage. The total charge collected by the collector and accumulated on the standard air capacitor and, hence, the voltage drop across the standard air capacitor are thus proportional to the total radiation exposure. The polarity of the voltage across the precision potentiometer is opposite

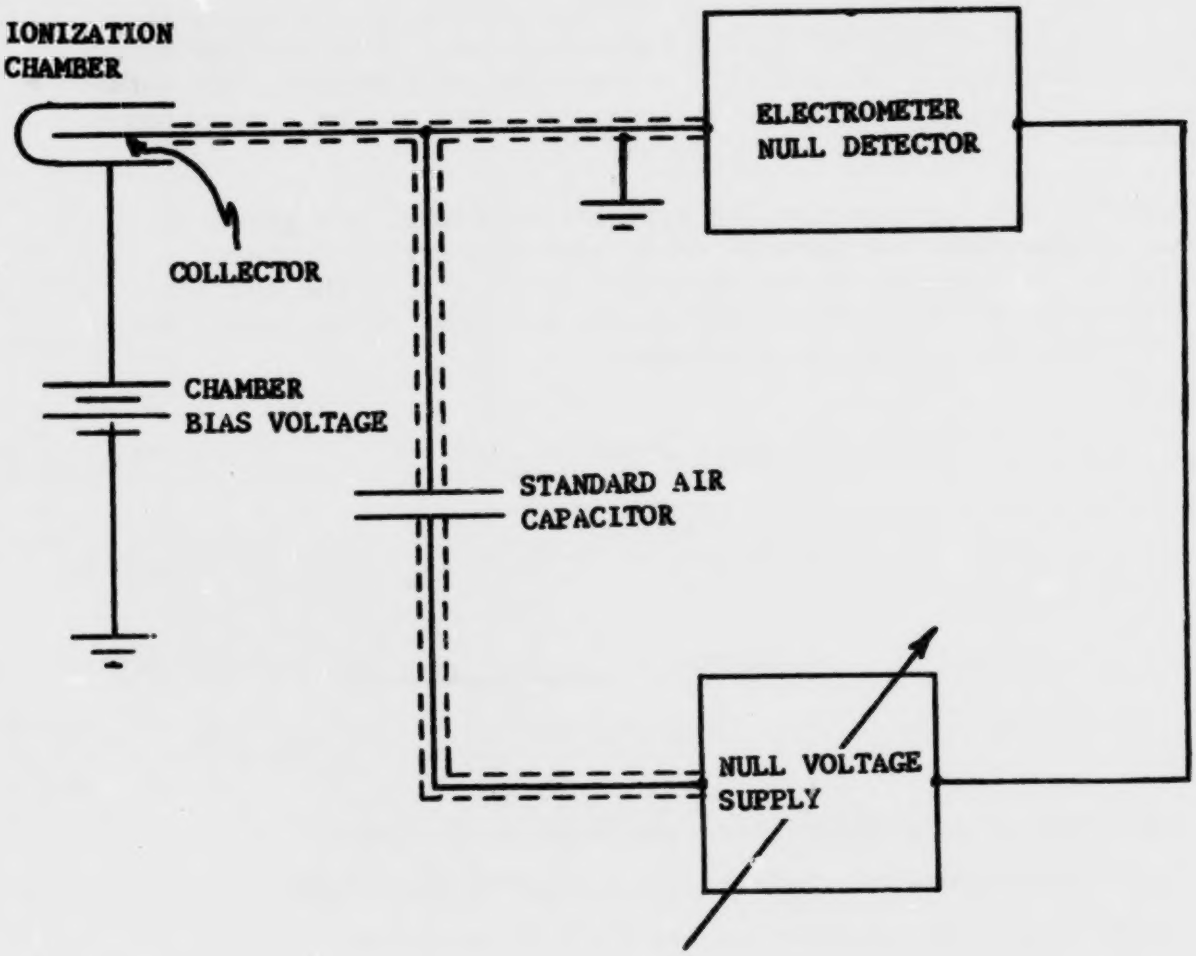

FIGURE 4. CHARGE COLLECTION AND MEASUREMENT SYSTEM

that of the voltage on the standard air capacitor in order that the net voltage across the capacitor-potentiometer series combination (the reading on the null detector meter) may be decreased as the output from the potentiometer is increased. When a null condition is indicated the voltage output of the potentiometer equals the voltage across the capacitor. This voltage may then be converted to an exposure using equation 4 (below), and into roentgens by using the energy calibration curve of the ionization chamber.

The calibration factors for the ionization chamber are given in terms of R/amp-min for various x-ray photon energies or beam qualities; therefore, it is necessary to interpret the voltage reading obtained from the potentiometer in terms of amperes. This is done with the following equations:

$$I\ (\text{amp}) = \frac{Q}{t} = \frac{C \cdot V}{t} \tag{2}$$

$$X\ (\text{R/min}) = I \cdot K_e \cdot K_{tp} \tag{3}$$

$$X\ (\text{R/min}) = \frac{C \cdot V \cdot K_e \cdot K_{tp}}{t} \tag{4}$$

where:

Q = Charge on standard air capacitor in coulombs.

C = Capacitance of standard air capacitor in farads.

V = Voltage from potentiometer reading in volts.

K_e = Calibration factor (including energy correction) for ionization chamber in R/amp-min.

t = Duration of exposure in seconds.

K_{tp} = Temperature and pressure correction factor.

The actual exposure rate can then be calculated using this method and compared with that obtained using the survey instruments to indicate the accuracy of their response.

Calibration Using a Cesium-137 Source. A popular technique used to calibrate survey instruments during field operations is to expose the instrument to a cesium-137 source yielding a known exposure rate and calculate a correction factor to be used for future readings. For this reason the instruments investigated in this work were exposed to an NBS calibrated cesium-137 source and their response characteristics noted. A calculation was performed to correct for the half-life of the source[4].

RESULTS

The five survey instruments investigated in this work were: a Victoreen 440, a Victoreen 440 RF, a Victoreen 444, an Eberline E500B with an end-window Geiger tube, and a Victoreen 1B85 Geiger tube incorporated in a scaler-timer system. Each instrument was exposed to an x-ray flux with exposure rate determined by the Shonka ionization chamber. The energy distribution function had been obtained with a lithium-drifted silicon detector and pulse-height analyzer for both the copper and the molybdenum radiators. Finally the instruments were exposed to a known flux from a cesium-137 source.

Victoreen 440. The Victoreen 440 is an ion chamber instrument. The ion chamber is a non-sealed air chamber with the front window constructed of two thicknesses of 1 mg/cm^2 mylar with a diameter of 8.9 cm. The chamber volume is 314 cubic centimeters. There is an aluminum-end cap supplied for beta discrimination.

The energy response for a Victoreen 440 at the specified energies is summarized in table 1. Of interest is the relatively high correction factor (actual/observed) for copper K-fluorescence x rays. The response of the instrument to molybdenum x rays and cesium-137 gamma rays is within the manufacturer's specification, ± 10% of the full scale reading.

Victoreen 440 RF. The Victoreen 440 RF is an internal ion chamber instrument. It has a 1 mg/cm^2 mylar window and a thin external magnesium window that is 8.9 cm in diameter. The chamber volume is 314 cm^3. It is reported to have a useful response over the photon energy range of 12 keV to 1.2 MeV.

A summary of the response characteristics for a Victoreen 440 RF when exposed to low energy x rays and a cesium-137 source is found in table 2. The response is quite accurate at the energy of molybdenum x rays and cesium-137 gamma rays. The instrument reads very low, however, when exposed to copper x rays. This was expected because copper x rays have an energy that is below the 12 keV lower energy limit specified by the manufacturer, and would be subject to considerable attenuation in the magnesium window.

Table 1. Summary of Victoreen 440 Response

Radiation Source	Energy of Radiation (keV)	Actual Exposure Rate (mR/hr)	Victoreen 440 Reading (mR/hr)	Correction Factor (actual/observed)
Copper radiator	8.05	106	63	1.68
Copper radiator	8.05	298	190	1.57
Molybdenum radiator	17.48	24.4	19	1.28
Molybdenum radiator	17.48	138	130	1.06
Cesium-137	661.6	11.3	13.5	0.84

Table 2. Summary of Victoreen 440 RF Response

Radiation Source	Energy of Radiation (keV)	Actual Exposure Rate (mR/hr)	Victoreen 440 RF Reading (mR/hr)	Correction Factor (actual/observed)
Copper radiator	8.05	198	82	2.42
Copper radiator	8.05	273	110	2.48
Molybdenum radiator	17.48	67	62	1.08
Molybdenum radiator	17.48	108	100	1.08
Cesium-137	661.6	11.3	12.2	0.93

The Victoreen 444. The Victoreen 444 is also an ion chamber instrument. The chamber has 1 mg/cm^2 mylar window that is 10.2 cm in diameter. The chamber volume is 237 cm^3. The energy response is stated by the manufacturer to be ± 15% from 6.5 keV to 1.2 MeV for gamma and x rays.

The response of the 444 at the three energies available for this work was very similar to the response of the 440 and the 440 RF. The instrument met accuracy specifications at 17.48 keV and 661.6 keV, but read low when exposed to 8.05 keV copper x-ray photons. This can be seen in table 3.

Eberline E500B with G-M Tube. An Eberline E500B was used with an end-window Geiger tube hand probe. The hand probe was a model HP-180A that uses an Amperex 200 NB G-M tube as the detector. The tube has a mica end window with a density of 1.75 ± 0.35 mg/cm^2. The protective grid at the window of the tube was removed to provide the best response possible. Care was taken not to saturate the tube, because the non-saturating characteristics of the E500B are voided when the HP-180A probe is used.

A summary of the energy response of the Eberline E500B can be found in table 4. The instrument was within manufacturer's specifications at 661.6 keV, but read consistently low when exposed to low energy x rays. It is also evident that the correction factor for this instrument has a marked exposure rate dependence changing from 1.82 to 2.98 correction factor at 55 mR/hr and 104 mR/hr respectively.

Victoreen 1B85. The Victoreen 1B85 is thin aluminum-walled Geiger tube with organic quenching. It has found popularity as a survey instrument probe and is used in the large area survey instrument[5] developed by Stoms and Kuerze of the Bureau of Radiological Health.

The 1B85 was used with a scaler-timer for data collection purposes. The tube was operated with a potential of 930 volts and was placed with its long axis perpendicular to the photon beam for maximum sensitivity. To avoid saturation of the Geiger tube it was exposed to a low intensity photon beam, the intensity increased until a counting rate approximately 75% of the previously determined saturation rate was reached. A Geiger tube is saturated when it is in a state of continuous discharge. The lowest exposure rate that will support continuous discharge of the tube is called the saturation rate. If a Geiger tube is operated at saturation, erroneous readings will result.

The results of exposing a Victoreen 1B85 to photons of three different energies can be found in table 5. The counting rate changed only slightly at each of the three energies but the exposure rates were quite different. The exposure rate for copper x rays was on the order of twice that of the other two exposures but the counting rate at this low energy was the lowest observed. This indicates that the energy response of the Victoreen 1B85 is far from constant in the 8 to 20 keV x-ray region.

Table 3. Summary of Victoreen 444 Response

Radiation Source	Energy of Radiation (keV)	Actual Exposure Rate (mR/hr)	Victoreen 444 Reading (mR/hr)	Correction Factor (actual/observed)
Copper radiator	8.05	338	218	1.55
Copper radiator	8.05	714	450	1.59
Molybdenum radiator	17.48	125	120	1.04
Molybdenum radiator	17.48	479	450	1.06
Cesium-137	661.6	11.3	13.0	0.87

Table 4. Summary of Eberline E500B with G-M Tube Response
(Probe Model HP-180A using an Amperex 200 NB G-M tube)

Radiation Source	Energy of Radiation (keV)	Actual Exposure Rate (mR/hr)	Eberline E500B Reading (mR/hr)	Correction Factor (actual/observed)
Copper radiator	8.05	100	55	1.82
Copper radiator	8.05	298	104	2.98
Molybdenum radiator	17.48	19.2	15.5	1.24
Molybdenum radiator	17.48	125	85	1.47
Cesium-137	661.6	11.3	10.5	1.08

Table 5. Summary of Response for a Victoreen 1B85 Geiger Tube

Radiation Source	Energy of Radiation (keV)	Actual Exposure Rate (mR/hr)	Victoreen 1B85 (counts/min)	$\frac{c/min}{mR/hr}$
Copper radiator	8.05	21.1	57,640	2732
Molybdenum radiator	17.48	7.8	65,624	8413
Cesium-137	661.6	11.3	62,728	5551

CONCLUSIONS

Frequently a situation will arise in the progress of a scientific endeavor or an industrial process in which one is confronted with necessity of determining the exposure rate produced by a radiation source. Any possible health hazard that may be associated with the source, be it an electronic product or a radioactive nuclide, must be identified. The determination is generally accomplished with a commercial-type survey instrument. This can be a valid procedure only if one considers and allows for the limitations of the instrument.

The response of a survey instrument can depend upon such factors as: ambient temperature and pressure, beam size, beam uniformity, beam intensity, and photon energy. The primary purpose of this paper was to investigate the response of five such instruments to photons in the low energy region. It was found that there was a definite degradation in the energy response characteristics between 17.48 and 8.05 keV for the instruments tested, although the Victoreen 440, 440 RF, 444, and 1B85, were adequate at 17.48 keV. Therefore, if one suspects that a significant percentage of the photons in a photon flux are of low energy he should be aware of the inherent inaccuracy of many survey instruments in this energy region.

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DISCUSSION

HERMAN CLARK (National Bureau of Standards): I would recommend, with any of these instruments, that it might be a good idea to use iron-55 sources to check your instruments. This puts out radiation approximately in the copper-molybdenum range, available in small and large areas with a very nice half-life. So if you have a small amount of this material on hand you can check your counters to make certain they are in proper operating condition and get an idea of equipment errors.

MR. ELS: That's certainly worth mentioning. Iron-55 has proven to be very useful for checking the response of instruments to low-energy x rays. It emits manganese x rays with energies in the 6 keV range. That is even lower in energy than the copper and molybdenum x rays used in this study. Iron-55 has a half-life of nearly 3 years, which gives the source a usable activity for many years.

MR. SHAW (Ford Motor Co.): In x-ray diffraction, often we are concerned with detecting leakage in very small beams. It is my understanding that many of these survey instruments, particularly ionization chamber instruments, respond quite differently when exposed to small beams than they do when exposed to broad beams or general scattering. It is misleading not mentioning this. Can you give us some results showing what sorts of errors you might expect when we do measure small beams?

MR. ELS: No, I cannot give any results on the response of survey instruments to small beams. The purpose of this paper was to discover how the instruments responded to low-energy x rays. To eliminate unnecessary variables, the experiment was performed under the nearest to ideal conditions available. This dictated the use of large, uniform beams that exposed the entire volume of the chamber to a uniform flux of x-ray photons.

There are formulas and procedures available to cope with the problem of small beams, primarily involving the ratio of the sensitive volume of the instrument subtended by the beam and the total sensitive volume. Some of these will be discussed in a paper to be presented later in the conference.

MR. BRILL(NAS, St. Louis): How would you convert from counts per minute to milliroentgens for the 1B85?

MR. ELS: The simplest way would be to use a factory calibrated survey instrument that utilizes a 1B85 as the detector. The readout meters for such instruments usually have one scale in counts per minute and another scale to read directly in milliroentgens. A more accurate method would be to expose the 1B85 to a source calibrated in terms of exposure rate, and correlate the reading in counts per minute to the known exposure in milliroentgens.

MR. BRILL: Also, what were the kVp values you referred to and why were they changed?

MR. ELS: The kVp refers to the operating potential of the x-ray tube producing the primary or exciting beam, and was varied as a method of changing the exposure rate from the radiator material producing the secondary or "useful" beam. It could have been done by changing tube current also.

DR. RUDMAN: I would just like to understand exactly how you know what radiation you had, at the time you monochromatized the radiation, to know that it was copper x rays? The 8.05 keV you indicate is the $K\alpha_1$ energy for copper, is it not?

MR. ELS: The photon spectrum from each radiator was determined using a lithium-drifted silicon detector and pulse-height analysis. The analyzer system was first calibrated using a radioactive source with emissions of known energy in the range of interest. Once the system had been calibrated it was a simple matter to determine what energies were present in the secondary beam.

DR. RUDMAN: And didn't you have radiation at higher energies as well?

MR. ELS: No, but what do you have on your mind?

DR. RUDMAN: You have white radiation at a higher energy of radiation. Did you filter this out with any filter system?

MR. ELS: I believe you are referring to bremsstrahlung radiation. There is a large amount of bremsstrahlung present in the primary beam, that is, the beam produced by the x-ray machine, but it is almost totally absent from the secondary beam emitted by the radiator material.

This is because bremsstrahlung is produced by the acceleration of a charged particle in the coulomb field surrounding a nucleus. There are no charged particles in the primary beam, therefore, no bremsstrahlung in the secondary beam except for a very small amount of scatter.

MR. R. HOWARD (Jones & Laughlin): I would just like to indicate that the conversion from disintegration rate or counts per minute to mR per hour is a strong function of the energy of the photon. I think that you should bear in mind this conversion is appropriate only for one rate of energy.

MR. ELS: You are correct, but I consider this problem to be the responsibility of the instrument manufacturer if he advertises his instrument as a "rate" meter. In most cases a correction factor versus energy curve is supplied by the manufacturer and should be on hand when a measurement is made. If an instrument reads only in counts per minute and a conversion to mR per hour is desired, the energy dependence adds another variable. It should be noted, in addition, that many instruments nominally reading in counts per unit time do not actually count descrete events. They merely measure current in arbitrary units called counts per minute. This makes care in the calibration process even more important.

MR. ROLAND JALBERT (Los Alamos): I have a number of comments. First of all, it is a pity that the instruments that you calibrated relative to the Shonka instrument had not been previously calibrated to known standards of cesium. In other words, if you hadn't set your instruments to read correctly to begin with, then when you use them at low energies and compare them to the Shonka you have a comparison there which probably, in some cases, was perhaps too small, despite the fact that the beam is too small in some cases and perhaps too big in others. I noticed that a lot of the instruments were reading higher than they should have when using a cesium source.

Another point I would like to make, with regard to GM-type survey instruments is that some of them will saturate at high rates in the sense that they jam and will read zero. So, when used in a very intense beam such as you might get from a diffraction unit, they will read zero instead of reading any positive amount, which will give you false indications of the hazards.

Also one should know if the instrument being used is of the newer type with the electronics that will not read zero if the tube is saturated when placed in a high field. I don't know about the 8500. I know the 8112 will not read zero when saturated, so I feel you are safer there. Anyway, you probably wouldn't want to use a GM unit in a high field because you wouldn't get a meaningful reading other than it is high, if it is properly designed.

The last comment that I have is about the Shonka. You said the window thickness was one-hundredths of an inch?

MR. ELS: Yes; 0.01 inch.

MR. JALBERT: Which seems just a little high for 8 keV.

MR. ELS: As I said in the paper, a calibration curve for Shonka chambers was obtained from NBS. This curve was usable down to about 5 keV, though it became nonlinear around 12 keV, and of course, the window thickness was accounted for in the calibration.

To get back to some of your other statements, you will recall that all the instruments had been calibrated using a cesium source. The instruments were not adjusted to give a "correct" reading when exposed to cesium, as you seem to be suggesting should have been done, because it was not considered to be a relevant technique. There is such a great energy difference between the cesium gamma rays and the low-energy x rays that a calibration at the higher energy would have no direct meaning at lower energies.

You also mentioned the possibility that the beam size was too small in some cases, but this is not true. In every instance the beam was determined by film measurement to be larger than the sensitive volume of the instrument. Therefore, the entire volume of the chamber was exposed to a uniform beam. This is the ideal case.

Finally, it is true that GM tubes can be saturated if exposed to a beam of high intensity. This condition was avoided during the experiment, but it is something that should be remembered when using a GM tube instrument.

MR. VILLFORTH: Excuse me. I think the point is well taken with regard to the GM instrumentation. I think it is bad to refer to this instrument as an E-500B, because that is the body of the instrument. Depending on what detector is used the results will vary. We are not talking about an E-500B. We are talking about a basic E-500B with a particular probe.

Also, some GM instruments have an internal probe for the high range. So, when you are on the high range, you may not be reading the detector in your hand, but the one internal to the meter. One would have to be careful of the interpretation of the meter reading.

MR. THOMAS: I am going to comment on the survey meter situation. I recently made a brief intercomparison of the Victoreen 440, an ion chamber instrument; a 1.4-mg/cm^2, 1-inch-diameter, simulated mica end-window geiger tube instrument; a 30-mg/cm^2 aluminum-wall geiger tube which happened to be the 1B85 of Ray Els' paper; and a 30-mg/cm^2 stainless-steel-wall geiger tube. The relative response was measured for x rays that I would have to "guesstimate" at between 5 and 12 keV. The measurements were made with the cover protecting the window of the Victoreen 440 and the end-window geiger tube removed, which is rather important. The metal-walled geiger tubes were exposed with their probe covers open but with the protective mesh in place around the tubes. The x-ray beam fully subtended all the detectors. The three GM tubes were used with the same associated electronics and had been calibrated to produce essentially the same response for high energy x or γ radiation.

The relative responses were as follows: The Victoreen 440 read 300 mR/hr, the end-window geiger tube system read 50 mR/hr, the aluminum-walled geiger tube read 10 mR/hr, and the steel-walled tube read 9 mR/hr. Frankly, even if the Victoreen 440 may be low by some 2 to 3 times, as Ray Els' calibrations showed, I was rather pleasantly surprised because I thought the variations might be considerably greater. If we overlook what the meter scale says for a minute, the readout characteristics of the instruments are such that each produced a readily seen, minimum level response to a low-energy x-radiation field of about 1/2 to 2 mR/hr. While the actual meter scale calibration is further off for the geiger tube instruments, their sensitivity is comparable to or better than the Victoreen, and the probe-type geiger tube instrument is much easier to use. It gives you a readily handled probe to wipe around suspect areas, where the ion chamber instruments may require a bit of a contortionist in some use situations.

The point I'm trying to emphasize here is that in most cases of protection surveys about diffraction equipment we really are doing a go/no-go type of survey. We are not trying to measure the radiation level in the direct beam because we really don't care what the direct beam is, only where it is. So, if you are approaching apparatus from a position where there is essentially no radiation, all of this group of instruments would start to respond at about the same point in a radiation field. This point is low enough as to read mR/hr to serve our yes/no survey needs. If the meter responds but doesn't go banging off the lower scale, the region in question is safe enough for any reasonable and necessary operations. If the meter goes banging off the most sensitive scale and perhaps the next most sensitive scale too, you really want to turn off the x-ray unit and figure out what's wrong before going on with the work. This means to me that these instruments can serve a valuable function, and they don't require highly skilled radiation measurements men to do the job. You have to remember that when the meter dial says mR/hr, that may be wrong; you may need a correction factor of 2, of 10 or 30 or more if you really want to know mR/hr. But for an awful lot of protection work you don't really care about mR/hr; you want an indication of where there may be a problem and help in locating and correcting the source of a problem. This is the very great value of these meters in operational radiation safety such as we are discussing.

MR. VILLFORTH: That is a very good point, John. I would emphasize it again.

You made some comment in your paper about the difference between exposure and dose, saying that we are really interested in the biological effect, which is the result of the dose delivered and not exposure in air.

While this is true, I am not sure that it is the complete story. In terms of an ongoing surveillance program, I think the measure of exposure is a satisfactory index to see if the operation is safe. In this regard, I think we can accept instruments that detect radiation even though they are not necessarily sophisticated enough to measure it. The GM is a good example.

I'm sorry we didn't evaluate the Bureau of Radiological Health's designed television x-ray monitor. I think it is an instrument that should have been looked at for its application to x-ray diffraction surveys. I think the array of GM tubes might have some application when you are searching for small x-ray beams. As I recall it is a 30-mg/cm^2 aluminum tube. But, nevertheless, it has the beauty of being able to sweep a large area.

So, you are looking for dose when you are looking at the bioeffects, duplicating an accident condition or trying to measure what the person may have received. You are looking for exposure as a quality assurance of the overall operation, and you probably are also looking at exposure in terms of the quality control of an industrial product. If you were the manufacturer and you were designing your equipment to a certain standard, you wouldn't design it to a biological standard; you would design it to an exposure standard. In other words, I think the instrument would be designed to produce no greater than an exposure rate of so many milliroentgens at a certain distance from the instrument.

MR. THOMAS: I hope I didn't come across in that way. I said that in preventative evaluations of these hazards we were looking for dose. We really are checking exposure. We are in complete agreement.

MR. SHAW (Ford): I know I am repeating myself, but I will have to disagree strongly with what Mr. Thomas said. He said that using these ionization chambers we come up and find no readings so we know it is safe. Yes, we do it, but with small beams. We can look at a very small, very high-energy beam with one of these meters and get no reading at all, so that we are getting a completely false sense of security using these meters in the way Mr. Thomas suggested. I would be very strongly against doing that.

MR. ELS: Your point is also well taken with regard to narrow beams. I think more will have to be said about that, and I hope the others will speak about narrow beams.

DR. ICE: I would just like to make one comment. I think we are leaving the people with a false sense of security on these survey meters. I think we must realize that we have a large area associated with them. If you want to take measurements of, let's say, the primary beam coming out of an x-ray diffractometer, you should go to some other type of instrumentation entirely, such as thermal luminescence dosimetry or something that you could get completely within the beam. You shouldn't be using these large-area-type monitors for this purpose. I would like to suggest, also, for these low-energy radiations that somebody ought to be taking a look at the plutonium probes that are being utilized now. They are very thin scintillation counters. I think the scintillation crystal is only about 1-mm thick. They are calibrated down for 17 keV. Here is an excellent instrument that can be used for survey purposes around one of these units.

VOICE: The problem of large area or large volume detectors isn't just the problem of broad beam. You very often get pinpoint leakage.

ROUTINE RADIATION MONITORING

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INTRODUCTION

Monitoring has been described in ICRP Publication 12[1] as "the measurement of radiation or radioactivity for reasons related to the assessment or control of exposure to radiation or radioactive material. The term includes the interpretation of the measurements." This same publication also describes the different types of monitoring, such as individual, routine, environmental, operational, special, and monitoring in or of the workplace, which is often referred to as a radiation survey.

The objectives of a radiation safety program are to provide for protection of the public, protection of the worker by maintaining safe working conditions, and protection of the employer. In the case of x-ray diffraction, there is no release of radioactive material and the low energy x-rays are very easily shielded, so that exposure of the general public should be insignificant. Thus, the safety of the worker is the primary concern in designing a monitoring program. A properly designed monitoring program will detect unsafe conditions in the worker's environment, will provide for the correction of such deficiencies, will show when safe conditions are present, and will document all of the above so as to provide the employer with a permanent record. Thus, the monitoring program serves to protect the employer from damage claims by employees or former employees and to document compliance with the applicable regulations. It is also very important that the monitoring program meet its objectives without any waste of manpower or resources.[1]

MONITORING PROGRAM

Records. Accurate and complete records of tests, measurements, surveys, inspections, personnel exposures, special investigations and other pertinent data are an essential part of the monitoring program and are usually required by law. Even records showing no radiation hazard are important because they document compliance with safety regulations and assure the worker that he is not being exposed to excessive amounts of radiation. For individual exposure records, form AEC-5 is recommended, because of the ready availability and convenience of use. This form or one containing the same information is required for the individual exposure records of Atomic Energy Commission licensees.[2] Thus, organizations which have both x-ray diffraction monitoring and AEC licenses would have individual exposure records in the same form. Also, most film badge processors supply exposure information in a format identical or very similar to the AEC-5 form. Separate records should, of course, be kept for doses to the whole body, skin, and extremities. Records of any special dose estimates or accident investigations should be filed with the routine exposure record.

The form used for radiation surveys of diffraction units should contain enough information to fulfill legal requirements and to be of value as a reference for comparison with future surveys. The work copy should be completed in such a manner that it can be used "as is" for the permanent record. A copy of the survey should be posted on or near the x-ray unit so as to be readily accessible to the machine operator. A typical survey form would contain the following information:

1. Name of the supervisor of the machine and any restrictions on use, such as key control.
2. Date of the survey.
3. Location of the machine including the room number and the position in the room (may be noted on the sketch).
4. Type of machine and identification such as model number, serial number, or special "in-plant" identification.
5. Description of the apparatus used with the diffraction unit such as cameras, diffractometers, x-ray tube type, special slits, collimators, couplings, etc.
6. Normal operating conditions such as maximum normal tube voltage and current, type of sample, the amount of time the x-ray tube is on, and the extremes of goniometer travel.
7. Special operating conditions for alignment, use with interlocks disabled, use without beamstop, etc.
8. A prepared drawing showing the machine and its location in the room, or enough space for a freehand sketch should be included. Locations at which the various radiation levels are measured and the areas of special attention are noted on the drawing.
9. Space should be provided for comments about monitoring requirements, restrictions on operation, and corrections necessary for routine use, such as changes in shielding or additional safety devices.

Preoperational check. A careful check of the operating controls, safety devices, and experimental apparatus should be made before the x-ray tube is turned on to perform the radiation survey. Those items which should be a part of the preoperational check are listed below.

1. Note the location and function of switches and indicator lights for electrical power, x-ray tube and shutters.
2. Unused x-ray tube ports should have adequate shields which are securely fastened in place.
3. Shutters should be checked for smooth, positive, and reliable operation.
4. Apparatus should be complete with no missing parts, especially beam stops, shields, couplings, etc. and parts should fit properly.
5. Viewing glasses should be in place and should be of lead glass.

6. Required shielding should be secured in place and not be simply wrapped around parts or held with cellophane tape.
7. Any modifications of the apparatus which could affect any of the safety devices or the radiation level should be noted.
8. Check for radiation damage or corrosion of parts exposed to the direct beam, especially plastic parts or close fitting metal parts in locations where air is not free to circulate and corrosive gases can accumulate.
9. The electrical system can also present a hazard and the power supply cabinet interlocks and the high voltage cables should be checked for defects.
10. Warning signs should be posted on the machine and surrounding area as required, but unnecessary signs should be avoided.

Operational survey. After completion of the preoperational check, the x-ray tube should be turned on and set for the maximum normal values of voltage and current. With all tube ports closed, the tube housing, shutters, and power supply should be checked for radiation leakage. Then the shutter of the port to be used should be opened and all parts of the camera or diffractometer checked for excessive radiation levels. Special attention should be given to beam stops and viewing devices and to any suspected area noted on the preoperational check. The area around the apparatus should be carefully surveyed in all directions, as scatter is possible at all angles.

The system should be operated with either a normal sample or a dummy sample in position and should be checked throughout the range of sample and detector orientations. The use of some diffractometers at negative angles can result in very high radiation levels in adjacent areas. Completely enclosed systems should be insensitive to such things as sample type and sample orientation. If the system is used without a sample for alignment, or in some other special way, that configuration should also be surveyed. Mechanical parts such as sliding shutters and couplings which have a number of possible positions should be surveyed throughout the range of travel. Warning lights and indicators should be operational, especially those designed to be "fail-safe".

Diffraction units which operate with more than one port in use at the same time should have the ports checked individually and in combination. All occupied areas adjacent to the machine should be surveyed. Very small beams of radiation may have to be located at the source and traced with a radiation detector to the point of actual measurement. While normal industrial construction of walls provides adequate attenuation of low energy x-rays, this cannot be assumed for partitions constructed simply of wood paneling, and occupied areas behind such walls should be surveyed.

INSTRUMENTATION

The exposure rate of radiation leakage and scatter from x-ray diffraction machines may vary from a fraction of a mR/hr to several R/hr and it may be in the form of small beams with a cross-sectional area less than a cm^2. A detector with small dimensions and fast response is needed to locate such small beams in the confined space surrounding the diffraction apparatus. An instrument with very good low-energy response is needed for actually measuring the exposure rate. A practical combination of instruments is an end-window GM detector with an audible indicator to locate stray radiation and a low energy ion chamber, such as the Victoreen 440*, for actual measurement of exposure rate. An audible indicator such as a headset or a speaker is necessary with the GM tube to provide immediate response and allow for more rapid surveys than when using the count ratemeter with a long time-constant. Use of the audible indicator also frees the surveyor from continuously watching the count ratemeter during the survey. A metal cover with a small hole in it for the GM tube will assist in accurately locating the origin of small beams of radiation.

Photographic film and fluorescent screens are sometimes useful for locating and determining the size of small beams. This is of value in determining if the primary beam is striking areas other than the beamstop. In such cases, leakage and scatter could be excessive. Fluorescent screens can usually only be used with the primary beam because of the relatively high exposure rate needed for detection. Using 50 kVp x-rays with a 1 mm of aluminum half-value layer , an exposure rate of about 5R/min was necessary to produce an easily observable image in a darkened room on a CdS fluorescent screen. Obviously, because of all the variables, this is only an approximation. Using the same x-ray source, a detectable image was produced on type 57 Polaroid** film with an exposure of 200 mR. Use of the same type film with fluorescent screens should substantially reduce the minimum exposure. This film is therefore useful for locating even low-intensity beams.

Measurement of exposure rates with a detector with a cross-sectional area greater than that of the x-ray beam will result in instrument readings less than the true value. If the beam area can be measured, an approximate correction can be made by multiplying the measured value by the ratio of the detector area to the beam area,

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* Victoreen Instrument Division, Cleveland, Ohio

** Polaroid Corporation, Cambridge, Mass.

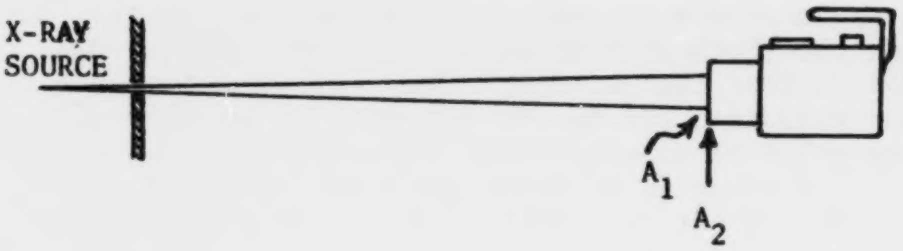
(see figure 1). This correction does not consider possible recombination losses in a small high intensity beam or corrections for electronic equilibrium, but it is suitable for most routine surveys. Another technique is to increase the distance from the x-ray source sufficiently that the beam area is larger than the detector. The measured value is then corrected for air attentuation and for the decrease in exposure rate with distance to the point of interest (see figure 2). However, air attentuation at very low energies is quite large and values for the absorbtion coefficients are not available in the commonly used handbooks. This technique is also of value if the exposure rate at the point of interest exceeds the range of the instrument.

Small organizations with only one or two diffraction units may not have radiation survey instruments available. In such cases, it is probably more economical to have a consultant perform the required surveys. However, the operator can usually perform radiation surveys for special applications or preliminary checks on new apparatus using the radiation detector from the diffraction apparatus, eg. GM tube, proportional counter, scintillation counter, photographic film. Film badges may be located at or in occupied areas near the diffraction unit to monitor the general radiation level. Accuracy is not of prime importance in measurements for routine monitoring, but it is important that the characteristics of the detector be known, especially the energy dependence, so that a reasonable approximation to the true values can be made.

PERSONNEL MONITORING

It has been recommended that personnel monitoring be provided for individuals who might receive doses in excess of 0.3 times the maximum permissible dose.[1] Even where doses to individuals are expected to be considerably below 0.3 MPD, a personnel monitor may be recommended. The monitor is useful in these cases to detect trends which may indicate a relaxation of radiation safety requirements, to detect unknown accidental exposures, to detect abnormal conditions, and to provide a record to show that employees have not received greater than the MPD.

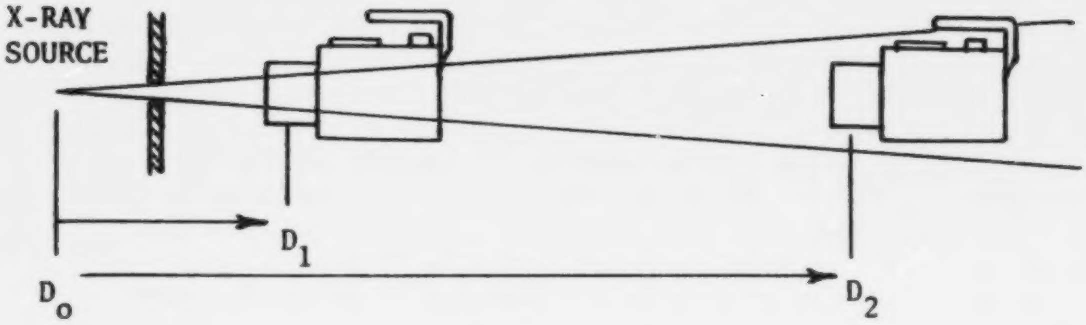
A film badge worn on the body is a satisfactory personnel monitor where large, homogenous radiation fields are encountered, as for persons working at some distance from diffraction units. However, operators of diffraction equipment may be unknowingly exposed to very small beams of high intensity radiation, including the primary beam. The probability of any personnel monitor intercepting such a beam is very small and accidental exposures may go undetected unless medical symptoms develop. Radiation burns from diffraction units have been confined almost exclusively to the hands.[3] Thus, the use of film badges worn on the wrist or fingers has been recommended to increase the probability of detection.[4,5] This assumption has not been documented, and in the opinion of this author, the use of wrist or finger badges for general use will not significantly increase the probability of detection of exposure to small high intensity beams. My major reasons for this conclusion are as follows:



$$\text{ACTUAL EXPOSURE} = (\text{INDICATED EXPOSURE})\ \frac{A_2}{A_1}$$

FIGURE 1

CORRECTION FOR SMALL BEAM



$$\text{EXPOSURE AT } D_1 = \text{EXPOSURE AT } D_2 \left[\frac{D_2}{D_1}\right]^2 \exp\left(\mu\,[D_2 - D_1]\right)$$

μ = linear attentuation coefficient for air

FIGURE 2

MEASURING HIGH DOSE RATE OR BEAM OF SMALL AREA BY INCREASING DISTANCE

1. Wrist and finger badges are subject to a greater variety of spatial positions than the body badge and in many positions are oriented so as to be completely shielded by the hand or wrist.
2. The wrist or finger badge has a high probability of being located on the wrong hand (the unexposed one).
3. Wrist or finger badges appear to be more inconvenient than body badges and are less likely to be used.
4. Even though the hands may be exposed to higher radiation levels by being closer to the x-ray source, the MPD for the extremities is greater than for the whole body or skin and compensates for this.
5. In the case of a large accidental exposure, the presence or absence of medical symptoms will probably be of more value than film badge data in determining whether an exposure occurred and the magnitude of the dose.

The above is not meant to imply that wrist and finger badges are not useful. In those situations where the operator is performing a routine analysis with no major changes in the apparatus, it should be possible to specify one type of dosimeter or a combination of several that will provide very reliable personnel monitoring with a high degree of probability of detecting an accidental exposure. However, research personnel or those operating a number of diffraction units are probably monitored as well as is presently possible by the use of a body badge. Body badges should not be worn on the belt if diffraction units are used which have table tops higher than belt height. Whatever type of film badge is used, the supplier should be notified of the type of x-ray source so that he can properly interpret the film badge data.

Photographic film has been the only widely used type of personnel monitor for low energy x-rays. Pocket chambers and pocket dosimeters are too energy dependent for use with diffraction units. Thermoluminescence dosimeters show some promise as x-ray dosimeters because of the good energy response of some of the available materials, but they have not been used extensively. In those installations where the dose rates are known and are constant, a calculated dose to personnel using the exposure time is satisfactory.

INTERPRETATION

As noted in the introduction, the interpretation of survey data is an important part of the monitoring program. Proper interpretation can make even cursory measurements valuable, while even the most complete radiation survey data is worthless if it is not used. The survey data should be analyzed and recommendations made to bring about or continue the safe operation of the diffraction unit and to insure compliance with the regulations.

The description of the equipment and the operating conditions, as noted on the survey report, should be checked for obvious conditions which might increase radiation levels. An inexperienced operator or one experimenting with a new configuration might not be aware of the use of excessive tube voltage or current, oversize slits or collimators, or mismatched couplings, which could cause high radiation levels around the unit. Recommendations should also be made for the correction of any deficiencies revealed in the preoperational check. Defects should be corrected at the earliest possible date and those which result in very high radiation levels in accessible areas should be corrected before the diffraction unit is used again. The need for additional shielding is dependent upon the exposure rate, accessibility, number of persons exposed, etc. Thus, it may be more important to shield a power supply producing radiation levels of 2 mR/hr in an area which is occupied than to shield a small beam of scattered radiation of 100 mR/hr directed into an inaccessible area. The supervisor of the diffraction unit should be free to choose the method by which defects are to be corrected so long as the desired result is achieved. The person conducting the radiation survey may be valuable in suggesting corrective methods which have been successfully used with other systems.

For routine operations, a detailed operating procedure should be developed which will minimize routine exposure and the possibility of an accident. This operating procedure should be posted on or near the machine where it is easily noticed by the operator. Whenever possible, interlocks to prevent exposure of the extremities to the direct beam should be provided.

It is obvious that interpretation of the radiation survey data involves considerable personal judgment. The legal requirements for leakage, posting, etc. must be met. However, simply complying with the legal requirements does not necessarily provide the safest environment for the worker. There should be no question that the dose to the individual should be as low as is "practically" possible. Even though personnel exposures are well within the permissible limits, there is little justification for allowing radiation levels which could be easily shielded, without restricting the use of the machine. There is likewise no excuse for the use of poorly fitted or defective shutters, collimators, couplings or diffraction apparatus, which result in increased radiation levels. Some of the things which should be considered in evaluating the radiation safety of a given diffraction unit are:

1. The integrated dose should be considered and not just the dose rate. High dose rates may be acceptable where exposure times are very short.
2. The size of radiation beams should be considered in addition to their intensity. It is seldom that an operator is motionless long enough for a very small beam to irradiate any one part of the body for a significant time. Averaging dose rates over an area, as is done for television sets (100 cm^2), gives a more accurate assessment of the hazard than the actual beam dose rate. This does not apply to the primary beam where dose rates are too high to allow such a technique.

3. The part of the body which could be exposed will determine the value of the MPD to be used.
4. The number of persons who could be exposed to stray radiation and their age, sex, and condition (pregnant) must be considered. Diffraction units operating in areas readily accessible to minors or non-occupationally exposed persons require frequent monitoring and the lowest possible radiation levels, if only to reassure the general public.
5. The restrictions on the use of the diffraction unit should be considered as part of any safety recommendation. Properly designed safety devices allow the diffraction unit to be used for all normal functions and those which are too restrictive will be defeated or ignored by the operator.

Moore and McDonald[4] have suggested that the radiation leakage from the tube housing be less than 25 mR in one hour at 5 cm and that stray radiation from the diffraction apparatus should not exceed 2 mR in one hour at a distance of 25 cm. They also recommend a limit of 0.5 mR in one hour at 5 cm from the power supply housing. These limits should be easy to achieve for most diffraction units. In fact, the low energy x-rays used in diffraction are so easily shielded that stray radiation from completely enclosed systems should be essentially zero.

Requirements for personnel monitoring should be specified in the recommendations resulting from the radiation survey of the diffraction unit. The use of film badges and the location where worn depends upon the application and has been discussed in the previous section. In general, all operators of diffraction equipment which has exposed beams and those persons who assemble and align systems should have some type of personnel monitor. This requirement is not necessary for those units which are completely closed, have no stray radiation and which cannot be operated with an exposed beam. The requirement for personnel monitoring may be reduced for those installations with a fixed configuration and which are frequently checked for stray radiation. Where personnel monitoring devices are required, it is important that checks be made to insure that they are being used. It is equally important that the data obtained by such devices be reviewed and evaluated. Increased exposures or exposures for individuals with no previous exposures should be investigated even though the value of the exposure is low. Such occurrences may signal an accidental overexposure, failure of a safety device, or an unsafe operating procedure.

CONCLUSION

The primary objective of the radiation safety program for x-ray diffraction units is to provide a safe environment for the operator. The monitoring program helps to achieve this objective by assessing the hazards, recommending corrective action and providing the proper documentation and records. A copy of the survey form with a complete description of the diffraction unit, the radiation levels, and monitoring requirements should be posted on the machine and another copy kept in the record file. The use of an end-window GM counter for detecting stray radiation and a low energy ion chamber for measuring it is recommended. Where regular survey instruments are not available, the detector for the diffraction unit may be used to locate stray radiation. The film badge worn on the body is recommended for general personnel monitoring, with wrist or finger badges recommended for special applications. Interpretation of the data from the diffraction unit survey and personnel monitoring devices is an important part of the monitoring program and requires consideration of many factors and much personal judgment. It is not enough that radiation doses to personnel simply be within the legal requirements; doses should be as low as is practically possible and recommendations for corrective action should reflect this.

REFERENCES

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2. Code of Federal Regulations, Title 10, Part 20, section 20.401.

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ADVANCED DOSIMETRY & EXPOSURE EVALUATION
(for X-ray Diffraction and Spectroscopy)

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THE PROBLEM

For most occasions, x-ray diffraction and spectroscopy users require simple monitoring and routine surveys. Elaborate procedures, sophisticated radiation detectors and/or expensive consultation are not routinely required. For persons involved in the design of analytical X-ray equipment and for those confronted with unexpected and possibly serious exposures to personnel, advanced dosimetry and exposure evaluation techniques do become necessary.

Equipment designers and accident analysts have, as their ultimate subject of concern, personnel exposed to analytical X-ray equipment. Both require, as a means to evaluate this subject, superior exposure information, i.e., advanced dosimetric data. Both will apply this information in a decision-making process that will relate the seriousness of the exposure to personnel, i.e., exposure evaluation.

ADVANCED DOSIMETRY

Significant exposure information contains, at least, elements of:

1. Quantity of radiation, and
2. Quality of radiation
3. Field Size

The quantity of exposure of X-rays is most commonly expressed in roentgens which term is limited in use to air. The term "rad" has a more universal applicability in that it may be used to describe the dose in any material. "Rem" is restricted to describing the dose in man and takes into account biological response factors. Most texts on radiation protection adequately cover the relationships between these terms and reference may be made to the ICRU reports.[1] For our purposes, quantity of radiation may be described in any of these units provided heed is paid to their limitations of applicability.

X-ray quality information relates the ability of an X-ray beam to penetrate materials such as shielding or human tissues. It may also be used to describe or predict variations in radiation detector response and variations in biological effects. Reference again may be made to standard health physics texts and the ICRU reports [1]. for detailed discussion.

Strange as it seems, measuring the quantity of radiation is far from a simple matter and the contents of the recent congressional hearings [2]. concerning X-ray emissions from color TV sets amply demonstrate this. Some problems encountered in attempting to measure X-rays from analytical X-ray equipment are:

1. The radiation may be non-uniform in intensity across an incident area,
2. May be small compared to the size of the detector,
3. May produce high exposure rate gradients across the detector,
4. May be so intense the response of the detector will become affected, and
5. May be so "soft" significant detection losses occur in the materials comprising or holding the detector.

These factors contribute to problems in performing measurements of X-ray emission and in specifying performance standards for equipment. The latter consideration is exemplified by the recent NCRP amendment [3]. which now specifies permissible radiation leakage from television sets in terms of a maximum rate averaged over a specified area.

The measurement of quantity of radiation is, hardly simple for those engaged in equipment design and demonstrating its compliance with performance standards. The reader is referred to several sources describing the problems and specific methods. [1, 4, 5]

For the person concerned with post-exposure analysis, as in an accident, measuring the quantity of radiation will usually be a simpler assignment than for the equipment designer. The prime reason is that the aforementioned factors affecting the precision of radiation measurements are frequently small compared to the variable of the man involved in an accident. Both equipment designer and accident analyst are concerned with human exposure. However, the designer's concept of the human role is theoretical and constant while the accident analyst's human factor is real and variable. To wit: The designer may be asked to provide shielding so that a person would not receive more than 2 mrem in one hour if he were continuously present. The assumption (a person is present) is prescribed and quite precise. Variations in measurements therefore can be significant. The accident analyst is frequently confronted by an individual who may or may not have accidentally put his hand in the primary beam at some indeterminate distance from the tube target for some inexact period of time. Notwithstanding the possibility of no exposure, the variation within these parameters frequently and greatly exceeds those of detector systems. Further, as we shall see, the most significant item for the accident analyst may be determining if an exposure occurred at all. Precise exposure information may be superfluous.

Exposure rate measurements require, as practicable needs, a detection instrument calibrated at the anticipated energy range, assurance of reasonable uniformity in intensity of the radiation incident upon the detector, assurance the radiation beam intercepts the entire detector or have provisions to correct readings if this is not the case, assurance the exposure rate gradient is not so severe as to introduce significant errors, assurance the exposure rate is not so high as to produce errors (e. g. recombination losses in ion chambers), auxiliary equipment to mount detectors, etc., beam catchers for shielding residual portions of the primary beam, elbow room, an understanding operator, and the patience of Job.

For the past several years, the Pennsylvania Department of Health has utilized thin window integrating ion chambers for measurements of analytical X-ray beams. Two models were used-651 (250 R maximum) and 576 (250 mR maximum), both manufactured by the Victoreen Instrument Company. For measuring primary beams, remotely held fluorescent screens are used to find a point where the beam is at least as large as the detector chamber (after a beam catcher is erected). Gradient and high intensity errors when using the 651 R-chamber are usually negligible if target to detector distances are 16 inches or more.*

We have also used film badges in a small study using 8.2 KeV X-ray and mixed 8.2 KeV and Co-60 gamma-ray exposures between 50 mR and 11 R. The reports of the two participating companies, neither of whom were informed beforehand of the exposures, agreed within ± 26% of our R-chamber measurements (6) for 10 of 12 exposures.

Solid state dosimetry is promising since the detectors can be quite small and may tolerate high exposure rates. Some care is suggested in their use without documentation of their response within the energy ranges encountered in analytical X-ray usage. Howley & Robbins (7) used TLD in the measurements of primary beam exposure rates. Of interest is the fact that their data reflects exposure rates far higher than previously reported for comparable operating conditions.

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*Based upon the manufacturer's specification of an intensity limit of 90 R/sec for a full scale reading and using Lindell's formula (See Reference 8) assuming a tungsten target at a 3000 Watt load (KvP and mA). The gradient percent change at this distance is 6% per cm.

If the tube target element, KvP, milliamperage and distance from the target to the point of interest is known, a reasonable estimate may be made of the primary beam exposure rate using the following formula (1):

$$(1)\quad \text{Exposure Rate in R/second} = \frac{50 \times \text{KvP} \times \text{mA}}{(\text{cm})^2} \times \frac{Z}{74}$$

where KvP is the peak accelerating potential in kilovolts

mA is the tube current in milliamperes

$(\text{cm})^2$ is the tube target to point of interest distance in centimeters squared

Z is the atomic number of the tube target.

Bo Lindell (8) reported this approximation correct to ± 25% between tube voltages of 25 to 80 Kv. Filters, he reported, may introduce a change of a factor of 2.

Our own comparison of the estimates by this formula with 17 measurements of primary beam exposure rates by 4 different persons involving 4 target elements, none or standard filtration and KvP's ranging from 20 to 50 KvP showed agreement within ± a factor of 3 for 14 of the measurements (Table 1). For the remaining three, one involved a non-standard filter and the other two were the aforementioned measurements using TLD.

An error of ± a factor of 3 is often tolerable in post accident evaluations where a quick estimate of exposure is required or where recreation produces large variations in exposure times and areas of exposed tissues.

Beam quality can be specified in a variety of ways. The ICRU (1) lists 8 types of specifications for describing the quality of machine produced radiation. An attenuation or spectral distribution curve are the most complete statements of beam quality possible. For our purposes, however, they are overly detailed. A statement of tube potential, on the other hand, rarely, if ever, provides sufficient information on beam quality.

Quite adequate information on beam quality for nearly all diffraction units and many spectroscopy units can be obtained by determining the tube target element. Under typical KvP application the prominent component of such X-ray spectra are the X-ray lines characteristic of the target element (Table 2). These lines are frequently sorted by selective filtration to produce an essentially monochromatic X-ray beam whose primary and only significant components are the K emission lines of the target element.

TABLE 1

Comparison of Measured and Calculated Exposure Rates

Target	KvP	Filter	R/sec-mA @ 5 cm meas.	R/sec-mA(5) @ 5 cm calc.	Ratio Calc/meas	Meas. Ref.
Cr	50	None	16	32	2.0	1
Co	31	None	76	23	.3	2
Co	31	Fe	32	23	.7	2
Cu	20	None	27	16	.6	2
Cu	20	Ni	8	16	2.0	2
Cu	35	None	22	27	1.2	1
Cu	35	None	40	27	.7	1
Cu	35	Ni	8	27	3.2	1
Cu	36	None	76	28	.4	2
Cu	36	Ni	26	28	1.1	2
Cu	40	None	50	31	.6	1
Cu	50	None	98	39	.4	3
Mo	36	None	17	41	2.4	2
Mo	36	Zr.	12	41	3.4	2

For above comparisons, Calc/Meas Range: 0.3 to 3.4

Target	KvP	Filter	R/sec-mA @ 5 cm meas.	R/sec-mA(5) @ 5 cm calc.	Ratio Calc/meas	Meas. Ref.
Cu	50	Va*	7	39	5.6	1
Cu	50	None	330**	39	.1	4
Cu	50	Ni	165**	39	.2	4

* Non-standard filter
** Measured with TLD

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TABLE 2

Common Analytical X-Ray Tube Targets & Filters

Tube Target	B-Filter & Thickness (mils)*		X-Ray Energy (KeV)
Cr	V	0.5	5.4
Fe	Mn	0.5	6.4
Co	Fe	0.4	6.9
Ni	Co	0.5	7.5
Cu	Ni	0.6	8.1
Mo	Zr	3.2	17
Ag	Pa & Rh	2.3	22

* To reduce $\frac{K\beta_1}{K\alpha_1}$ to $\frac{1}{100}$

The exception to the above are spectroscopy units utilizing white or continuous spectrums, typically from tungsten targets at 50 KvP. For such cases, and those where tube target elements are unknown or there is reason to question assumptions of the beam quality, absorption curves may be prepared using calibrated aluminum beta absorbers available from a nuclear science laboratory, or, in a pinch, aluminum foil. (Fig. 1) Sufficient attenuation measurements should be made to determine HVL and TVL thicknesses. (Table 3). The ratio, TVL/HVL is the fall-off ratio (F.O.R.) and is a measure of the monochromatic nature of the beam. The closer the F.O.R. is to 3.32, the nearer the beam is to being monochromatic.

Paper estimations of exposure quantity and quality are possible using Bo Lindell's formula for estimating exposure rates in the primary beam and knowledge of the tube target element. Such estimates frequently will provide sufficient information for evaluating an accidental exposure to the primary beam.

If more precise information is desired, actual measurements of beam quality and quantity may be performed using thin window R-chambers or film badges and aluminum absorption filters. (Fig. 2) Appropriate target to detector distances and exposure times may be estimated beforehand based on the range of the detector and using Lindell's formula.[8] A suggested exposure range for film badge detectors is 50 mR to 200 R. The need for air absorption corrections should be checked.

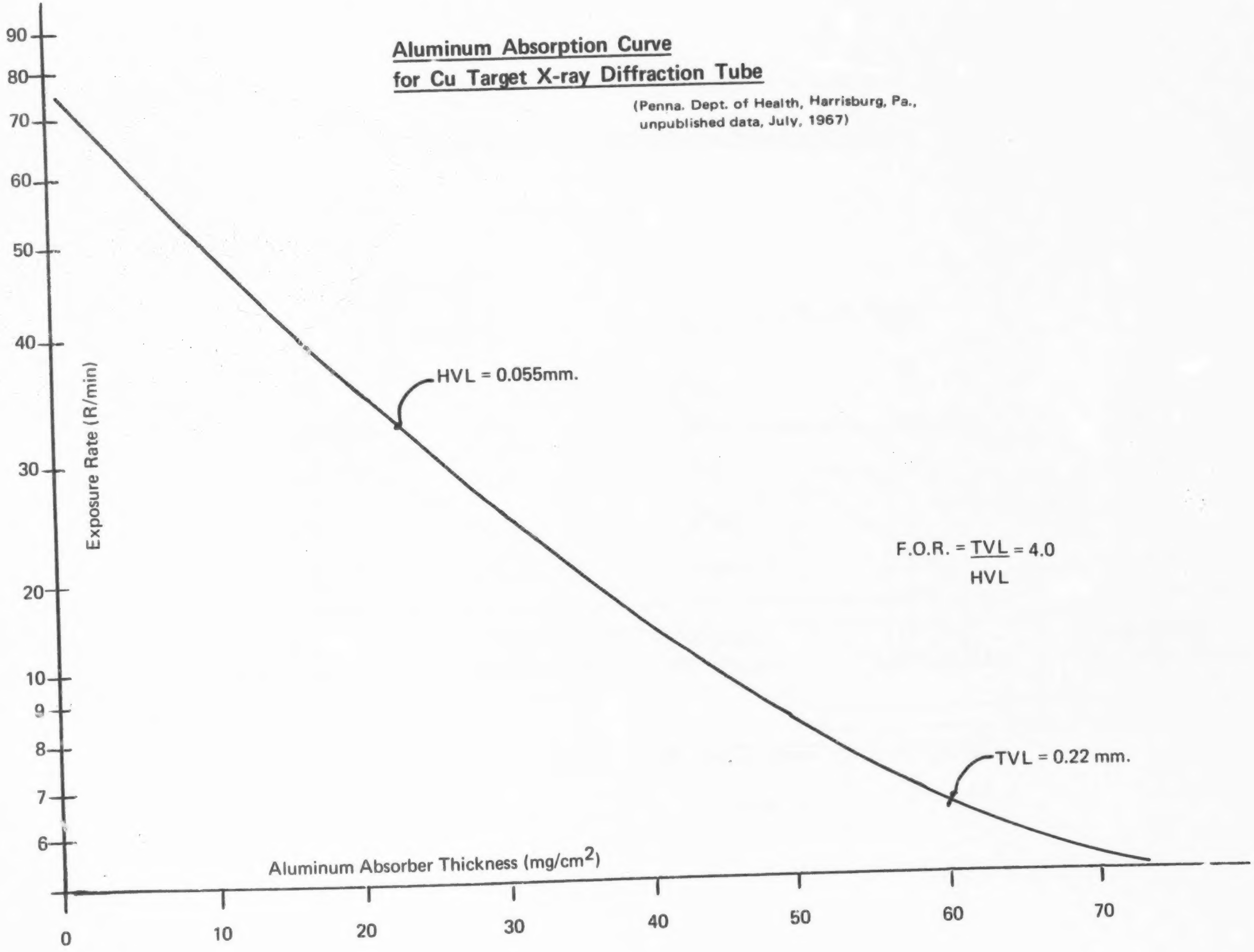
MAN-MACHINE INTERACTION

Before proceeding with the advanced dosimetric information to an evaluation of an exposure, it is necessary to understand the interaction of the man with his machine, specifically, what did the man do with the analytical X-ray unit that led to an exposure? Frequently, non-routine activities, overlooked during design of equipment, during safety reviews and in operation planning, become instrumental in accidents. Such activities include alignment procedures, special techniques requiring temporary modification of equipment and subsequent compromise of radiation protection and safety, maintenance operations and repair work. All are predictable, controllable activities.

Alignment procedures may be non-existant, simple, or complex, depending on the sophistication of the equipment, its use and its operator. Simply, it requires aligning the X-ray beam emerging from the tube with the tube head port, with the sample, and for the diffracted X-rays, aligning the detectors properly. Techniques include light optics (eyeballing and using telescopes), electronic counting (testing alignment with X-ray emission between adjustments), using fluorescent screens or combinations of the preceeding. Poorly located adjustment controls such as thumbscrews requiring the arching of the wrist and hand over an open X-ray beam may be encountered.

Special techniques requiring modification of equipment, maintenance and repairs are activities bearing a common characteristic: Safety

Figure 1



Aluminum Absorption Curve for Cu Target X-ray Diffraction Tube

(Penna. Dept. of Health, Harrisburg, Pa., unpublished data, July, 1967)

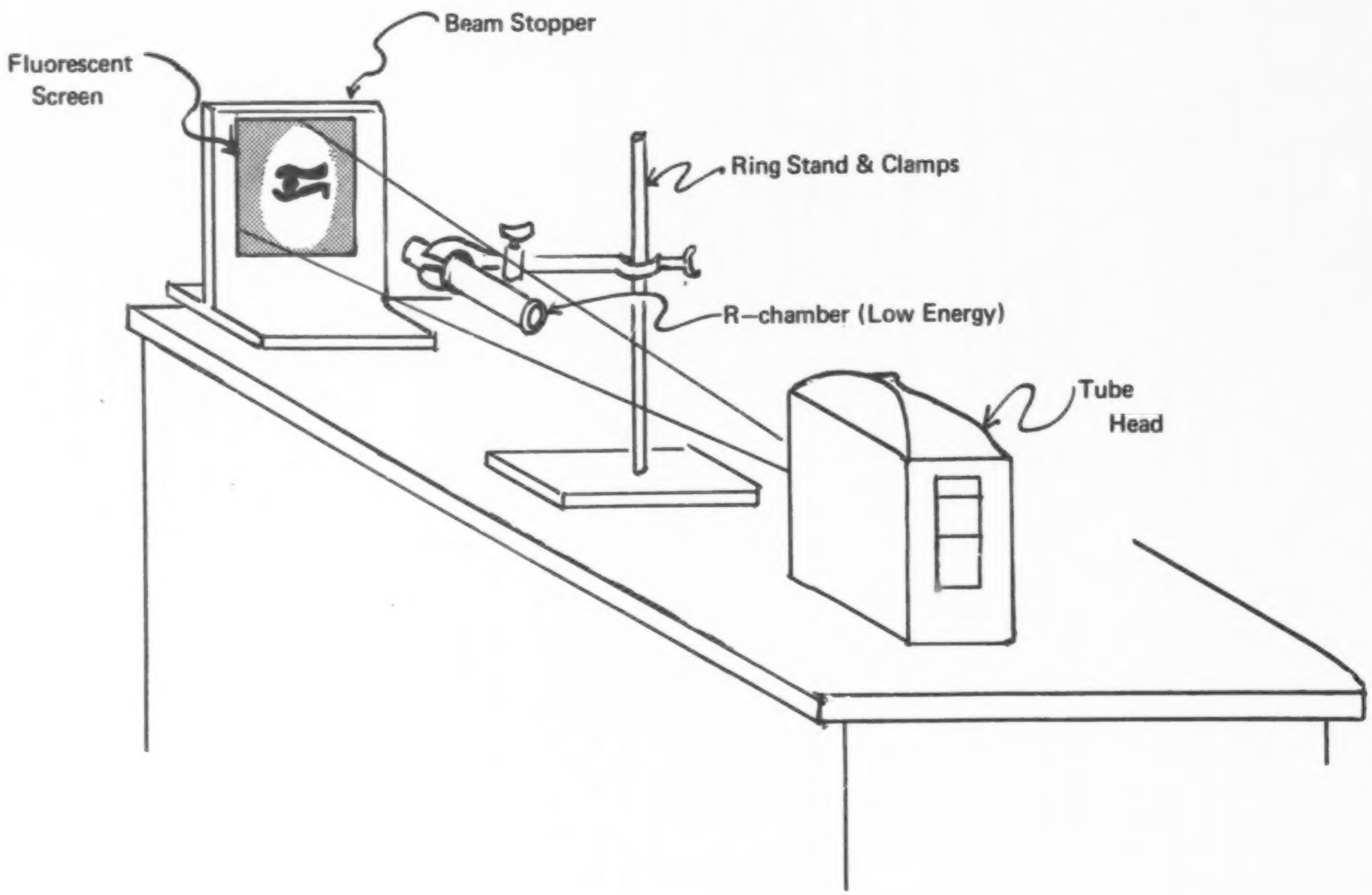
TABLE 3

Theoretical X-Ray Beam Quality Factors

X-ray Energy KeV	Aluminum HVL (mm)	Muscle HVD (g/cm^2)	Muscle TVD (g/cm^2)	Fall-Off Ratio (TVD/HVD)
10	0.097	0.14	0.46	3.3
15	0.34	0.51	1.7	3.3
20	0.81	1.3	4.2	3.3
30	2.9	4.5	15	3.3
40	7.3	10	34	3.3
50	15	17	56	3.3

Figure 2.

Exposure Rate Determination Using R–Chamber



mechanisms and procedures may be aborted, become inoperative, or are simply inadequate. Switching from a diffraction tube head to a spectroscopy tube head on a combination two tube unit by switching power cables seems innocuous until two or more operators are involved, there is no indication of which tube is connected, and no communication between the operators. (Fig. 3) Dusting the analyzing crystal of a fully enclosed, lazy-susan interlocking spectroscopy unit is no problem except when it's performed by opening a side cabinet door that isn't interlocked and with the X-rays on. (Fig. 4)

These and other (9) examples demonstrate the essential need to understand man-machine interactions if adequate equipment design or accident analysis is to be performed. The most elaborate dosimetry is of little value if the manner of the exposure is not understood.

Perhaps no instance of understanding man-machine interactions will be as difficult as that time when an accident, or suspected accident, is recreated. The discovery of an accidental exposure may be 3 to 5 weeks past the time of occurrence if physical symptoms or personnel monitoring reports are the first or only clue. Recreation, therefore, may unsuccessfully tap an individual's recollection of events a month old and quite likely nearly undifferentiated from yesterday's. Additionally, there may be no witnesses to corroborate the circumstances. Equipment failure, if implicated, may be impossible to document as to the time it first occurred. Lastly, locating the sites where a primary beam impinged upon an arm, wrist or hand rapidly moving about adjusting goniometer settings and sample holders will be a challenge, at least.

The real value of understanding man-machine interaction, of course, is not in post-exposure evaluation but becoming aware of potentially hazardous situations followed by preventative action.

EXPOSURE EVALUATION

John Doe reports to his supervisor that he believes he may have accidentally exposed his forearm to the primary beam of an analytical X-ray unit. A small area of reddening is, indeed, apparent on the suspect forearm. Although unsure that the suspected sequence of events actually occurred, he believes it occurred within the last month. Recreation combined with dosimetry suggests a possible exposure to 800 to 1100 roentgens of 8.2 KeV X-rays, certainly consistent with the observed biological reaction. Whole body film badge reports are not helpful in that they do not report unusual exposures but would not be expected to.

This information is conveyed by the supervisor to the plant physician. Several weeks later, the supervisor is informed no X-ray overexposure occurred and the skin reaction was a chemical dermatitis. What happened, of course, was subsequent questioning of the operator and medical tests revealed exposure to a chemical which, in the course of some spillage, fell on the skin and caused a reaction.

Figure 3.

Man-Machine Interaction-Changing Tubes

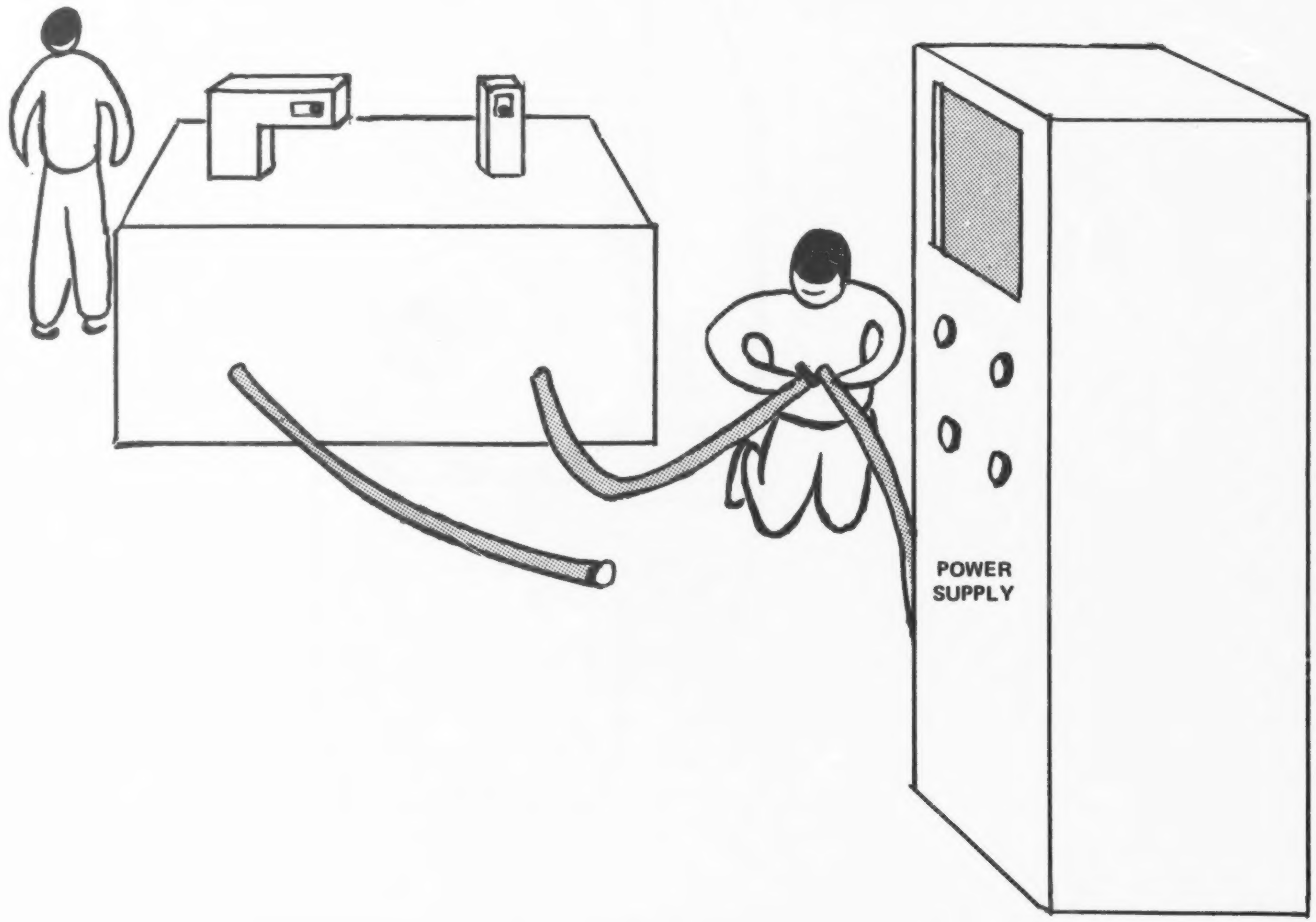
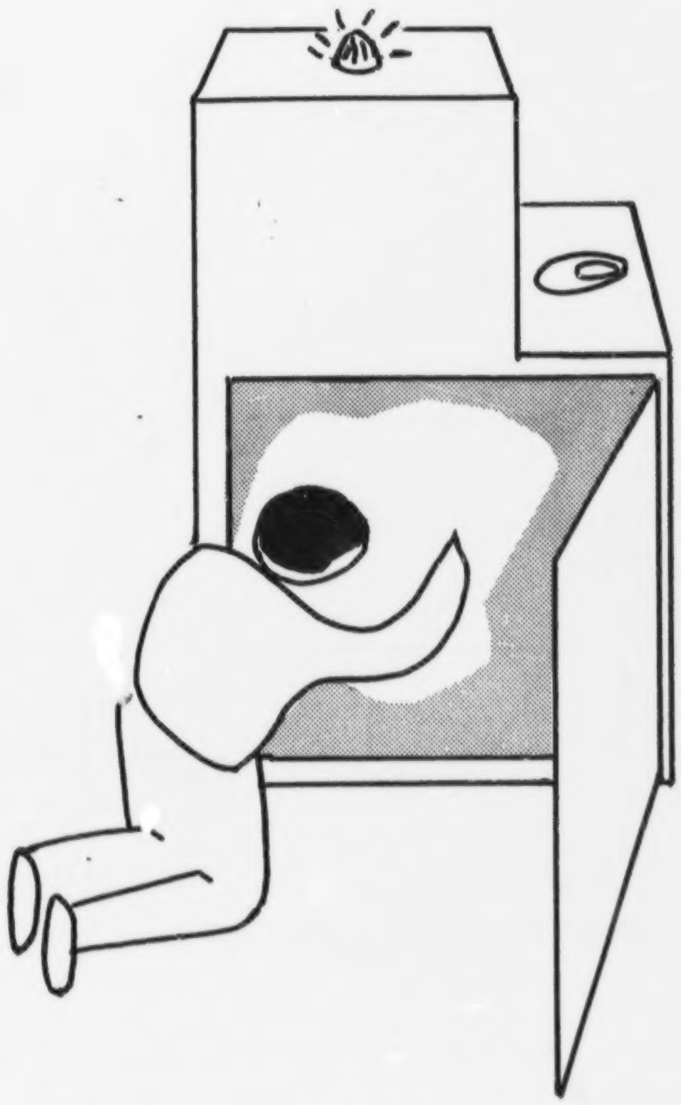


Figure 4.

Man-Machine Interaction-Dusting the Analyzing Crystal



The lesson of the example is that whatever dosimetry is performed, that information, including conclusions, is not binding and must be examined for consistency and agreement with other data, e.g. physical examination data, comparison to reports of similar accidents, the condition of the involved equipment, etc. This examination of data constitutes exposure evaluation.

Did an exposure occur? If the data supports an affirmative answer, what information is there as to the degree of exposure? What dose value shall be assigned for purposes of legal documentation? Having established an exposure occurred, was it preventable? What action is deemed suitable to prevent its recurrence? What shall be the future of the exposed individual?

These are questions the answers to which constitute the evaluation of an exposure. They are the loose ends which must be tied up following an accident. Who decides the answers?

The ultimate decision making will occur at a level of corporate management and at a location in the managerial scheme peculiar to the facility involved. The contributors to the decisions may include the exposed individual, supervisory personnel, and representatives of the insurance carrier, the medical department, the union, the legal department and management. Consideration of reports of outside consultants and of regulatory requirements may prevail.

Radiation accidents are comparably rare. Consequently, the activities following an accident are neither well established (except for regulatory considerations) nor are past practices well known. It is suggested, then, that persons performing advanced dosimetry also assume a responsibility of assuring adequate exposure evaluation; specifically to assure that consideration of all facts pertaining to the situation takes place and involves all persons potentially affected.

SUMMARY

Advanced dosimetry requires measuring the quantity and quality of radiation in accordance with the available radiation detectors and their limitations and in accordance with the needs of the situation. Gross calculated estimates may be quite sufficient in some instances. Precise measurements may be required in others.

Exposure evaluation requires an understanding of the man's interaction with the equipment and understanding the needs for adequate decision making on questions of occurrence of an accident, degree of exposure and future action

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DISCUSSION

DR. SAMSON: Has anybody calibrated a scintillation counter against mR? I think this would be very desirable to know to have some correlation between the number of counts you get in the scintillation counter and milliroentgens. Then you can take the scintillation counter and monitor your unit. If somebody has done something like that, I think it would be very desirable to have the table.

Also, I think when considering dosimetry one should distinguish between leakage and secondary radiation. I noticed this morning that when speakers were referring to the term leakage, they in many cases meant the secondary scattering from the beam trap, from the sample, or from the beam. Leakage, I think, should be determined as x rays escaping directly from the source.

You see, now one has a much better basis for legislation.

I personally feel that leakage is inexcusable. Secondary scattering from behind the collimator, sample, beam trap, and so on, is excusable, and I think one should draw a definite distinction here. Leakage can easily be reduced to zero levels, but we cannot do that with secondary scattering.

MR. VILLFORTH: Very good. I hope the regulators will take that into consideraiton in developing standards.

Regarding the first question, does anybody have an answer to this? This is the same point that was raised by Dr. Ice.

DR. ICE: Eberline makes a "plutonium" probe, which, according to their manufacturing bulletin, comes with a calibration curve (energywise) for the probe. Although it is specific for the 17-keV plutonium x ray, they do show a calibration curve on up to 50 keV and say that the detector is capable of detecting 50 keV; I think it goes down to about 5 keV.

MR. SIDNEY PORTER (Radiation Management Corporation): Rod, I just would caution you to remember that that particular probe is very temperature sensitive. If you had calibrated it at 80 degrees, you can't use it for 50, or you are far off.

MR. SHAW (Ford Motor Co.): There is another source of danger. That is that with some types of constant-potential energy generators, if you switch the power tube of some of these generators off, the circuits will remain charged, and you get a slow discharge inside the tube. But, if you switch the generator off and at once start removing the shielding, or something, you can get quite a substantial dose of radiation directly onto your fingers. I think not too many people are aware of this.

MR. O'BRIEN (Brookhaven): There have been a number of remarks made about lead foil or tin foil being used for wrapping around the tube. I would like to speak for tin foil. I think it is a very effective shield, although it may not look so pretty and we don't have to be proud of it. But it does serve the purpose, and it is usually better than none.

The alternate solution would be to pull the machine apart quite precisely, with all the little baffles in it, and it is quite unlikely that you are going to get an operator to do this.

DR. SAMSON: The disadvantage of the tin foil is that it is not a permanent cure of the actual problem. You can have that, if you have some specific objectives that Dr. Young yesterday described. It is all right. But as soon as you have an apparatus that is going to be used by 20 different people a year, I think you are never sure. Someone comes in and the tin foil drops on the floor because the scotch tape that held it loosened in the meantime, for instance, and then you have the leak again. I think that it is not a temporary cure of the actual problem.

Another point is that there should not be any leakage in the first place because it indicates a faulty design of the equipment. And there is no excuse for designing the equipment in such a way that you have leakage. A person who puts together an x-ray tube and a coupling, and so on, in such a way that it leaks indicates that he doesn't know how to do a good job.

I think commercial equipment that is being bought should be tight. There is no excuse for having a leak in the first place.

MR. VILLFORTH: I would also point out that some of the reports that were mentioned today are available through our office. There are two more, "A Summary Report on X-ray Diffraction Equipment," and "Radiation Safety Recommendations for X-ray Diffraction and Spectographic Equipment." If you don't have them and if you would like them, plus the one on color TV, give us your name and tell us what you want.

SESSION D

GUIDES, STANDARDS, AND REGULATIONS

Moderator: Robert O. Gorson
Stein Research Center
Jefferson Medical College

UNDERSTANDING GUIDES, STANDARDS, AND REGULATIONS
Robert O. Gorson

REGULATOR'S VIEWPOINT
John C. Villforth

MANUFACTURER'S VIEWPOINT
W. D. Ashby

THE USER'S VIEWPOINT ON X-RAY DIFFRACTION SAFETY STANDARDS
Stanley Block, Ph.D.

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UNDERSTANDING GUIDES, STANDARDS and REGULATIONS

Robert O. Gorson
Jefferson Medical College
Philadelphia, Pennsylvania

In order to gain perspective on the presentations which are to follow, we want to try to distinguish in our minds the difference between regulations and guides and standards. In our case, we are discussing radiation guides and/or radiation regulations.

In the field of radiation protection, the earliest guides or standards in this country were formulated by what is now called the National Council on Radiation Protection and Measurements (NCRP); and as a result of these guides, certain standards became widely used in this country. These standards or guides can be broken down into several categories. First of all, we have those guidelines which we call design standards. The design standards are intended primarily for people who manufacture radiation-producing equipment, or in other words, the manufacturer.

Secondly, after equipment is designed, constructed and put into use, then a different type of standard takes over; these are so-called "performance standards." The performance standards have to be consistent, of course, with the design standards so that if a piece of equipment meets certain design standards, it shall automatically meet corresponding performance standards. But, in order for someone to be able to inspect and check a piece of equipment in the field, it is frequently easier and more practical to use performance standards rather than design standards. So, performance standards are not only for the manufacturer but also for the inspector, or person who actually tests the equipment.

Finally, there is another set of guidelines or recommendations which is primarily for the user. These are standards of good practice. These have been developed primarily for the person who actually uses the equipment.

In the radiation area, the first guides and recommendations in this country were formulated about 1929 by the NCRP. Ever since 1929, the NCRP has periodically produced reports, guidelines, and standards in various aspects of radiation safety. All together, there are some 36 reports that have been produced.

On the international level, the corresponding committee is the International Commission on Radiation Protection -- it has been in existence since about 1929. More recently, the International Atomic Energy Agency has produced a number of handbooks and guides. In addition, there is the World Health Organization.

It wasn't until rather recent years, the last decade, that there were many regulations covering the field of radiation protection. But gradually, many of these standards which had been developed earlier and had been modified from time to time have been promulgated in the form of regulations.

In the field of regulation, we have a number of regulating agencies. The most important one, as you are well aware, is the Atomic Energy Commission, particularly where radioactive materials are concerned. Another important one is the U. S. Public Health Service, particularly the Bureau of Radiological Health. You will hear more about that later. Of course, there are all the other Federal agencies.

Coming down to the State level, we have the State departments of health. In some instances, such as in Philadelphia, we have the City department of health.

The governmental agencies, in many instances, have taken the guidelines and standards produced by other organizations. For example, in the United States, besides the NCRP, there is the National Academy of Sciences, the American National Standards Institute, and several other organizations which have guidelines and standards pertaining to radiation protection.

Some of these, particularly those having to do with design standards, have been adopted and sometimes modified and adopted by the AEC, the Public Health Service, and the Federal Radiation Council which serves as the advisor to all the government agencies.

Some of the guides and standards cannot be used in the form of regulations, particularly many of those concerned with good practice. Good practice involves judgment, and it is very difficult to legislate good judgment. So, many of the recommendations of the various advisory boards remain as guides to good practice but cannot be made regulations because of the difficulties in writing a regulation which involves judgment, because it is difficult to anticipate every situation where the judgment has to be used.

During this afternoon's discussion, the speakers will be referring to one or the other or perhaps both of these different types of guidelines or regulations. It is worthwhile to remember to make a distinction between these two because there are many important differences.

REGULATOR'S VIEWPOINT

John C. Villforth
Bureau of Radiological Health
Public Health Service
U.S. Department of Health, Education, and Welfare

The subject I am to discuss is regulation from a "Regulator's Viewpoint." I want to make it clear that since there are several agencies involved in radiation regulation, I am going to be talking about the responsibility of the Department of Health, Education, and Welfare.

I should call your attention to the fact that most States also have responsibilities. Some of these States have been regulating radiation users a lot longer than has the Federal Government. I believe that 42 of the States and Territories do have some form of regulation which could be construed to encompass analytical x-ray equipment. To those of you in industry or universities who do not know your State radiation control program, I suggest that you make a point to meet their personnel and find out what responsibilities you might have to them and how they can help you.

I think the subject of regulation is inadequate, because regulations are really the tools of an agency. They are not an end in themselves, and sometime we forget the purpose of regulations. The purpose of our regulations in the Bureau of Radiological Health is the reduction of unproductive radiation exposure and the protection of the users in the general public.

When we have to resort to enforcing compliance with regulations, you have failed in industry, or we have failed in some aspects of our program. It is much better if we can solve the problem, whatever the problem might be, by a system of voluntary activities and voluntary compliance.

The Bureau of Radiological Health, or its predecessor organizations, has been involved in radiation protection since before the advent of much of the recent controversy over fallout from weapons testing. This, however, gave impetus to radiological health at the Federal level in the Department of Health, Education, and Welfare.

We had been involved in radiation protection on a broad basis by various means. For example, we have had a research grant program which stimulated research to solve some of the unknown bio-effects and dosimetry problems. We have had a training effort which recognized that one of the most important means to a good radiation control program was by having trained people out in the field. And we have supported this effort through training grants to institutions, thereby making stipends available to individuals to continue graduate training in radiological health.

We have had short-course training courses available since the 1950's. We have given specific courses that pertain to analytical x-ray equipment, industrial x-ray uses, etc., which I think have been valuable to the State and industrial people who have participated in them.

We have involved ourselves in State programs by assisting the States who have had direct regulatory responsibility for solving the problem.

We have had a technical staff which has worked with various professional groups and various advisory standards committees. Several of our members are on the working group of the American National Standards Institute, Subcommittee 43.1, working with Mr. Block on analytical x-ray equipment. We have had liaison members on just about all of the regulatory groups that Mr. Gorson has just discussed.

I believe that this multiplicity of effort is the way we can get the job of radiation protection done. However, any program needs a catalyst to assist in the reaction, and our catalyst came from the Congressional interest stimulated by the color TV radiation incident. After the 8 days of hearings before the Senate and House Committees on Commerce in 1967 and 1968, the Senate concluded that experience has shown that although voluntary standards are helpful, they are not adequate to guarantee compliance by all involved.

And, thus, on October 18, 1968, the Radiation Control for Health and Safety Act was passed. The Act gave the Department of Health, Education, and Welfare responsibility for reducing the exposure of the public to all unnecessary and hazardous radiation from electronic products. This was to be done basically by two ways: first, through the establishment and the administration of performance standards; and, second, through the undertaking of research and investigations and the development of efforts for controlling this radiation. On June 4, 1969, the authority for administering this legislation was delegated to the Bureau of Radiological Health.

I think it is important to understand what is covered under the definition of an electronic product. It includes x-ray diffraction, x-ray spectroscopic, and other analytical x-ray equipment, and all devices which produce radiation; that is, either x rays, particulate radiation, or sonic, intrasonic, or ultrasonic waves. In other words the definition covers the whole electromagnetic spectrum and sonics.

The heart of the Act is the performance standard for an electronic product. These are standards to control the emission of electronic product radiation from such products as the Secretary of HEW determines must be controlled to protect the public health and safety. These performance standards may include provisions for testing of the product for the emission of radiation. They may provide for warning labels and signs. They may provide for the inclusion of instructions for the installation, operation, and use of the product.

Industry has been quite concerned that these standards do not become design specifications and inhibit the future development of a product. The Act is very specific that this should not be the case and that these are standards for the performance of the equipment which are directed primarily at the emission of deleterious electronic product radiation.

There is the typical case with which you are familiar -- x-radiation emission from color television. The performance standard for color television was promulgated in the Federal Register on Christmas Day of 1969 and is effective January 15, 1970. In this performance standard the industry is to restrict the leakage of radiation from color television receivers to less than 0.5 mR/hr at 5 cm from any surface of the set. This is the kind of performance that I am talking about.

In addition, if you look at the color television standard, there is a requirement that the manufacturer must label all the critical components in the set and identify their operating characteristics. This is the labeling and warning aspect of the standard. And it is conceivable that a performance standard for analytical x-ray equipment might be concerned not only with the radiation emission but also with adequate labels, warnings, and identification.

I mentioned that a performance standard may include provisions for installation, operation, and use of the electronic product. It seems possible that as you develop good standards for the user, whether they are within the framework of ANSI or within the crystallographic groups or the Health Physics Society, they might be required to be included with the sale of each item. I don't know if this is the way it will be done, but this is something that would certainly have to be considered.

Of course, we can't enforce the manner in which a product is used, but we can require the manufacturer to provide instructions for use. I think these are important points that are sometimes overlooked in the understanding of the Act.

In the whole evolution of a performance standard, we are admonished that we must give consideration to the latest available scientific information and data. And, of course, we are going to look to groups who have developed and who have given a lot of consideration to this subject to give us guidance on some of the details of a performance standard.

We will have to take into consideration currently recommended standards. Certainly, we must consider ANSI 43.1, if it is published, as well as such documents as NCRP 93 and some of the foreign publications.

A performance standard must also be tested for its reasonableness and technical feasibility. This caused us a problem with the early drafts of the color TV standard. It was felt that it was not technically feasible to lower the leakage radiation limit to below 0.5 mR/hr at 5 cm to the original suggested recommendation of 0.1 mR/hr. This was not acceptable because in order for industry to provide TV sets with emissions of less than 0.5 mR/hr, their quality control program would have to produce sets with emission well below that amount. And they would need to have instrumentation capable of measuring significantly below 0.1 mR/hr. Since such instrumentation is not presently available, we decided that it would be more feasible to keep the emission level at 0.5 mR/hr and make the conditions of testing more stringent. That is, effective January 15, industry is to test the sets with the user controls in their worst condition; e.g., with a barely viewable picture. As you recognize, the user controls, such as contrast, do affect the exposure rate. On July 1, the same exposure rate would be applicable, but this time with the service adjustments at their worst adjustment, thus maximizing leakage radiation. Effective July 1971, the standard will require that the emission rate of 0.5 mR/hr not be exceeded when certain components are malfunctioning. It is possible for a particular tube to fail but still to give a viewable picture, but because of the failure, the voltage on some other components may be increased, thereby increasing the leakage radiation. The manufacturer's testing program would have to demonstrate that under these conditions of use the emission level would still not exceed 0.5 mR/hr.

We felt these conditions were very reasonable, and we felt that this would provide adequate protection to the public.

Any performance standard promulgated by the Secretary must first be presented to the Technical Electronic Product Radiation Safety Standards Committee for their consideration. This is a 15-member committee made up of five representatives from industry, five from government, and five from private walks of life, who are experts in their own right and who will advise the Secretary on such considerations as technical feasibilitity, reasonableness, etc., of a proposed standard.

So, it is through the concept of a performance standard that we can protect the public from excessive exposure to electronic product radiation; and the performance standard will be developed through consultation and advice from various groups. In the case of analytical x-ray equipment, this will involve many of the people that are sitting here in this room. We can also protect the public if there is a significant health hazard by invoking the defects section of the Act. This could result in the manufacturer either repairing, replacing, or refunding the product, depending on what the Secretary of HEW deems appropriate. That is the enforcement side of the regulatory program and should only be used if all other means of radiation protection fail. I prefer that we use the voluntary program and that we work with industry without getting into this phase of compliance. But, as Congress had pointed out, experience has shown that voluntary standards are not always adequate to guarantee compliance for all involved.

There is also a provision under the Act for an annual report which must be made to Congress. Included in that annual report is a thorough appraisal, including statistical analysis, estimates, and long-term projections, of the incidence of biological injury and effects, including genetic effects, to the population resulting from exposure to electronic product radiation.

In support of this, there is another provision which requires that a manufacturer of electronic products shall report to the Bureau of Radiological Health all excessive radiation occurrences reported to or otherwise known to such manufacturers which arise in the manufacture, testing, or use of any electronic product offered for sale. What these two requirements call for is a registry of incidents. This will allow us to acquire more information on bioeffects and to understand something about the cause of the incident. The latter information can then be incorporated into a future performance standard.

We are about ready to announce in the various journals involved with electronic product radiation and to inform various professional groups of the establishment of a Radiation Incident Registry. In the meantime, I ask for your cooperation in providing the Bureau with this kind of information.

Let's look at a possible timetable for an analytical x-ray equipment performance standard. Keep in mind that there are 35 million items in use in the United States which are classified as electronic products. This is a $24 billion industry. The greatest number of electronic products are in such consumer products as color television receivers. There are about 24 million color TVs. There are estimates that there are up to 5,000 analytical x-ray devices out in the United States and that between 1,000 and 2,000 units will be sold in the next 3 years.

We hope that we can move into the analytical x-ray area reasonably soon, but I think to a large extent it will be based on the assistance that we get from you people. We would like to rely on the expertise of people like you who have taken the interest to come out for these 2 days to review some of the problems that are being presented here. We hope you will go back to your respective committees, to ANSI, to the American Crystallographic Association's Apparatus and Standards Committee, and reexamine what needs to be done and expedite your timetables. Make available to us the benefit of your thoughts so that we can develop intelligent and enforceable standards. We hope we can get into those standards some of those provisions that you have talked about today, those provisions of instructions for users, instructions for installation, and so forth.

Please, go back and give consideration to what has been said here for the last 2 days, and advise us of your thoughts. We have some of your thoughts on the record here. We are going to have to go over these and sift through them and then get together again with some of you. We need your help. We want to do it right and intelligently.

MANUFACTURER'S VIEWPOINT

W. D. Ashby
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Picker Corporation
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One might expect, in a conference such as this, for the manufacturer to take a more conservative position or to offer the opposing view in a debate on the need for or acceptance of Guides, Standards, and Regulations. Although I officially speak for one manufacturer only, I will present the position, however, that most manufacturers support endeavors such as this conference and welcome the advice and counsel which is derived. I am disappointed that there aren't more manufacturers represented here. I think the show of hands this morning indicated that there are only three manufacturers represented. I also take the position that most manufacturers have already taken a responsible role in trying to provide safe equipment.

These efforts, however, must be made in parallel with the efforts of users, and this has been continually brought out in this meeting. Ray Young yesterday illustrated and discussed some very pertinent examples - and typical examples I might add - of equipment modifications and marriages which could complicate the efforts of the manufacturers.

For example, just visualize what could result from the marriage of a Picker generator, a G.E. tube and housing, Siemen's diffractometer, homemade shutters and control, Phillips' detector and pre-amp, RIDL electronics, and so forth. This is specifically what Ray showed.

Aside from the radiation aspects and coordinated interlocks, a serious electrical hazard could result. None of these manufacturers have designed their equipment to be electrically compatible with each other. We don't know what strange feedbacks might occur in such a combination. We might all be using different concepts in line filters, grounding networks, and so forth. It is quite conceivable, then, that in the event of a ground fault in one of the lines, a serious electrical shock might occur if one touched two of the components simultaneously. I am not trying to be critical of Ray, because I know Ray well and his setup down there. He has always done a very excellent and thorough job of marrying equipment and paying attention to the potential problems. But a casual marriage of this type, or one where these kinds of considerations were not taken into account, could be a disaster.

The point is that we as manufacturers need the users' help and cooperation just as the users need properly designed and built equipment to begin with. Really, the only totally safe piece of equipment is that which can't be turned on and which can't be reached, because even turned off, one might fall over it.

Therefore, assuming that we recognize the need for codes and support them in general, let us discuss what manufacturers consider to be essential for workable codes. First, however, I would like to digress to the differentiation between guides, standards, regulations, rules and codes.

I get confused when I go to Mr. Webster's publication and I read that a guide used as a noun is something which provides a person with guiding information and, used as a verb, it is to regulate and manage. Standard means something set up and established by authority as a rule for the measure of quantity, weight, extent, value, or quality. The regulation is an authoritative rule dealing with details of procedure. And a rule is a prescribed guide for conduct. It is also a regulation or a by-law governing procedure or controlling conduct. A code is a systematic statement of a body of law, especially one given statutory force, and it is a system of principles and rules.

It appears that the significant property of these definitions is the interchangeability of the terms and the use of each as a synonym for others. In many respects, trying to differentiate these meanings is of academic interest only and the basic intent becomes lost. I would rather consider the impact upon the manufacturer of a set of standards, using the word standard to refer to an established set of performance limits within which products are expected or intended to comply. We should then consider that there are two types of safety standards: 1. mandatory, which are established and administered by some governmental agency at the federal, state, or local level; and 2. recommended, which may be prescribed by a voluntary standards association such as ANSI or the ACA Standards Committee or by the manufacturers themselves.

In the past, a completely different implication was assigned to each of the above types of standards. The mandatory standards were, of course, enforceable and carried various degrees of penalty for non-compliance. On the other hand, voluntary standards or recommended standards too often have been interpreted loosely or even ignored. There have been some notable exceptions in adherence to voluntary standards, however. Among these are the NCRP Report 33 for the radiation aspects of medical radiation equipment and Underwriters'

Laboratories for electrical safety. I think there is one outstanding reason for the wide compliance with the recommendations of NCRP 33 and the voluntary subscription to U. L. within the x-ray industry (other than the fact that U. L. listing for x-ray equipment is now required by several large cities). This reason comprises the theme of my remarks concerning the manufacturers' viewpoint of guides, standards, and regulations.

Specifically, the reason is the adherence of the above standards to a set of criteria which I propose as being essential to any useful and acceptable standard. In other words, for a set of safety standards or recommendations to be useful and workable to a manufacturer, they must fulfill the following conditions;

1.) They must be realistic -

Safety Standards should allow an affirmative answer to the following questions: Are they needed? Are they relevant to the safety of the product? Do they provide the basic safeguards needed or are they merely an attempt to shift responsibility? (By the same token, the responsibility cannot be shifted from the manufacturer to the user.)

2.) They must be specific -

The standards should be worded in such a way that manufacturer, user, and enforcement agency all have the same interpretation of the individual requirements and the conditions under which the requirements apply.

3.) The performance specifications must be measurable -

The quantitative data necessary to determine compliance must be within the limits of routine measurement. I feel that this is one of the most important criteria for radiation safety standards. Remember that the final test of compliance is made at the user's site after installation and the measurements must be ones that at least can be confirmed in the field by non-experts with reasonably simple instrumentation.

4.) The standards must be non-restrictive to further design and technical advances.

In other words, the safety standards should specify performance criteria and not design criteria.

5.) The standards should be consistant with other standards and requirements, not only domestic, but international as well. As this group well knows, most manufacturers of highly specialized equipment such as x-ray diffraction and fluorescence instrumentation must attempt to compete in the world market. Conflicting requirements, however, remove the advantage of the larger market and result in higher prices to the user.

The criteria for workable standards just presented are obviously quite impressive and difficult to accomplish. However, more than ever before, efforts must be made to provide safety standards which satisfy these requirements as far as possible. And that, in fact, I repeat, is the reason I think that NCRP has been successful in gaining wide acceptance on a voluntary basis from the manufacturers and the manufacturers quite rightly voluntarily subscribe to UL evaluation and listing. Encouragingly, the very presence of this group and the opportunity for me to make these comments is indicative that just such efforts are being made.

Formulating safety standards for x-ray diffraction and fluorescence equipment is particularly difficult because of the nature and complexity of the equipment and because of the fact that much of the use made of the equipment is for non-routine or experimental analyses.

On the other hand, the need for safety standards satisfying the criteria outlined has been emphasized quite drastically within the last 16 months. In October, 1968, Public Law 90-602, the Radiation Safety Act of 1968, was passed. This Act not only requires the promulgation of safety standards for radiation producing equipment but requires that existing specifications and standards shall be used as the standards under the Act until the official ones are adopted. This means, of course, that standards derived as a result of this conference or published by such groups as ANSI not only would have a significant influence on the requirements specified by the Bureau of Radiological Health, but could be the legal standards for an indefinite period of time.

In conclusion, it seems to me that vague recommendations to the manufacturers do not and can not accomplish the end result. Intelligent, specific directions can and will result in safe products.

ADDITIONAL COMMENTS

Although my talk has ended, I thought I might take just a minute here and comment on some of Dr. Samson's remarks (see page 193). Although I think some of Dr. Samson's statements illustrate a position where these standards must be specific and where good directions must be given, I might take exception to the one comment that there is no excuse for any leakage. In other words, the leakage should be zero.

To begin with, that is theoretically impossible. I am not nitpicking. His intent is well meant, and the leakage should be an insignificant number. But my point is, what is that insignificant number? That should be and has to be specified.

So, I think that this illustrates my point, in that very definite values have to be specified. Without them, the manufacturer is in quite a dilemma, and I think regulatory agencies are in quite a dilemma also.

We have every intention of cooperating and complying with the regulatory agencies, and I am sure they do with us. When neither one of us knows what we are trying to accomplish, I think we are both in trouble.

THE USER'S VIEWPOINT ON X-RAY DIFFRACTION SAFETY STANDARDS

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Users of x-ray diffraction and fluorescent analysis equipment cover a wide range of training, experience and interests. At one extreme are those with little formal training, carrying out repetitive tasks on the same equipment day after day. At the other extreme are the research scientists pushing the equipment to its limits and carrying out experiments which require great accessibility to the useful beam and the samples. One type can suffer injury from ignorance, the other from disdain, and both from carelessness. Standards must protect all classes of users from faulty equipment and, as much as possible,from their own carelessness. Perhaps to cover all possibilities standards should be written assuming two classes of users. Those in figure 1, unfortunately, have members from all classes of users (present company not included), but everyone thinks he is included in figure 2.

The two most important considerations for diffraction and fluorescence analysis equipment are safety and accessibility. All equipment, when properly used, should be completely safe. At first thought this can always be achieved by enclosing the equipment in lead-lined boxes, but this would frustrate any research and be self-defeating. In attempts to utilize the equipment fully, scientists could remove the safeguards and place themselves in danger. Therefore, equipment for specific repetitive tasks should be designed emphasizing safety. There is equipment (i.e., some fluorescence analysis equipment) which carries out its designed tasks and is safe enough to be used in this lecture room. Equipment designed for research purposes, on the other hand, should give equal consideration to accessibility. Precession cameras, for example, should be open in structure because it is relatively common to add high-temperature and low-temperature accessories. For such cases, I realize as a user, I have a responsibility to safeguard myself and my technicians by proper training. The technical training should include sufficient physics so that the user is aware of the theory of operation of the equipment and the probable results of modifications. Teachers, in addition to training their students in the physics and chemistry involved, should emphasize the hazards as graphically as possible. Very rarely does a textbook on x-ray diffraction and fluorescence and analysis discuss safety. If the user does not accept responsibility for proper training, the only alternative is to design the equipment for users in figure 1 with safeguards enough to make it "idiot proof." Then the danger will be conscious defeat of the safeguards to carry out "the" experiment, and the ultimate possibility of a radiation injury.

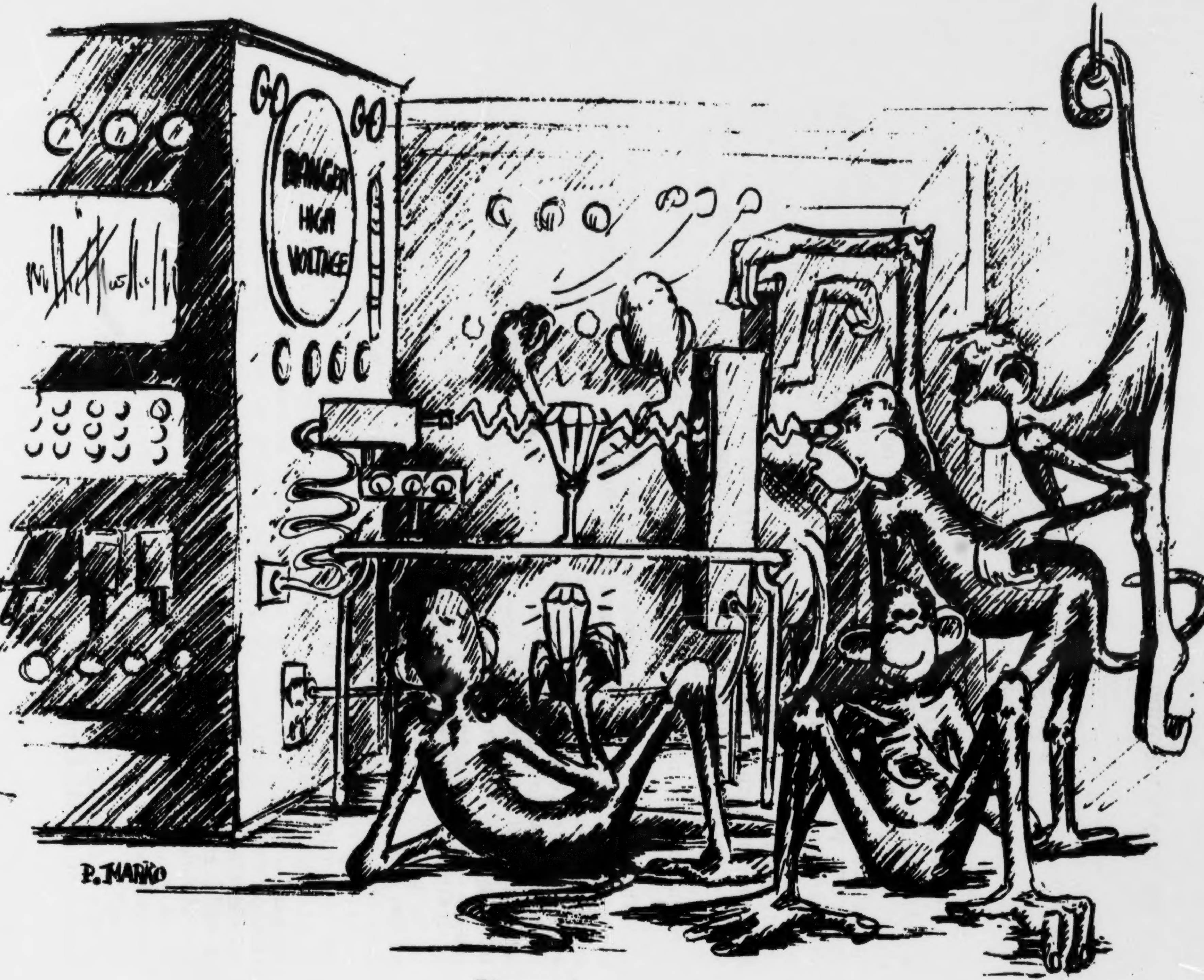

Figure 1

NOT REPRODUCIBLE

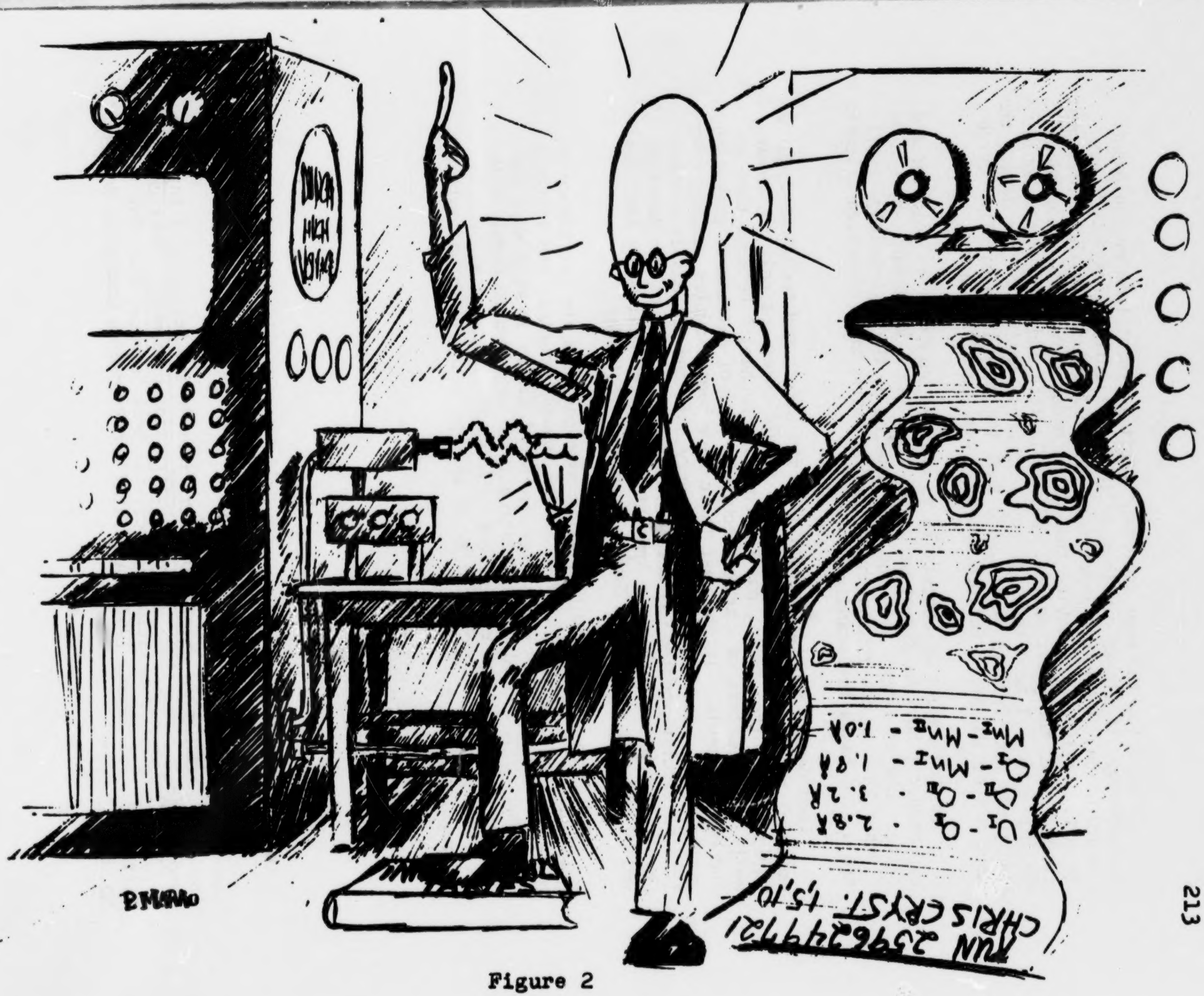

Figure 2

NOT REPRODUCIBLE

As in life, the most important trait I expect from my equipment is honesty. If lights or other indicators signify "x rays on" they should be on. Even more important, if the light is off, the x rays must be off. Failure of a device that is intended to warn of a hazardous condition is the great danger. All indicators and safeguards should be fail-safe. I mean that for any reasonable failure of the device the equipment must fail in such a mode that the user is safe. The device need not be immune to failure but must fail in a safe mode.

Another aspect of honesty is to deliver only what is paid for and expected. I buy the direct or useful beam and I don't want any add-on extras such as x-rays from the tube housing or the high-voltage rectifiers. This is one reason why radiation limits and not design criteria are a good basis for standards.

Good design should consider both the safety and technical requirements of the user. The requirements should cover not only the x-ray equipment and the camera, but the coupling mechanism between them as well. The shutters or coupler should be free of extraneous radiation and easily usable. In the past there have been examples ranging from easily usable and highly unsafe to very safe and not easily usable. This particular problem was well covered in a report of the American Crystallographic Association Apparatus Committee chaired by Karl Beu[1] and by the talk Prof. Sten Samson gave here yesterday.

One final point I would like to make concerns the prevalence of radiation regulations that are slanted towards reactors and isotopes. The hazards associated with x-ray equipment differ in many ways and x-ray equipment should not automatically be required to comply with all previous radiation regulations. Obviously, in cases of overlap, i.e., when x rays are generated by an isotope source, the appropriate AEC regulations apply.

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[1] Beu, K.E. (chairman) Safety Considerations in the Design of X-ray Tube and Collimator Couplings on X-ray Diffraction Equipment. American Crystallographic Association, Polycrystal Book Service, P.O. Box 11567, Pittsburgh, Pa. 15238, 1962. (Apparatus and Standards Committee Report No. 1), 12 pp.

QUESTION AND ANSWER SESSION

MR. GORSON: At this point, we will open up the session to questions from the audience. Please identify yourself, by name, and your institution.

MR. INGLES (Frankford Arsenal): For the first time today, I heard a legislative value for radiation protection of 0.5 mR/hr. I would assume that this is going to be a common value for all these new regulations?

MR. VILLFORTH: Absolutely not. We are not responsible for setting standards for users; we are responsible for setting performance standards for equipment. And, as a part of these performance standards, we are going to develop a method of testing that equipment to see that the radiation does not exceed some limit. You see, that number that the industry must design for is a testing number; for color TV it is 0.5 mR/hr at 5 cm from the surface of the set. For x-ray diffraction equipment we may come up with another exposure rate at some other prescribed distance from the device. This may be directed at the tube leakage. This specific number should not be confused with an exposure to an individual, although the value was derived from our concern for the health and safety of the individual.

MR. INGLES: In other words, you later will have a whole new series of standards for the other equipment?

MR. VILLFORTH: Yes. We have one, for example, for TV receivers; it is 0.5 mR/hr at 5 cm from the set. We are now working on one, a performance standard for cold-cathode x-ray tubes used for educational purposes, and we are proposing a value of 10 mR/hr at 30 cm from the tubes. The point is that these are test numbers based on the population that is exposed, how often they are being exposed, at what distance they are being exposed, et cetera. We would not expect that the number for color TV receivers would be used universally as a leakage number for any electronic product. We will have to consider many factors in developing the number which we set for a performance standard.

DR. BLOCK: In the American National Standards Institute standards that we are developing, we have used as a basis the NCRP recommendation. For the general public, the number we have used, I think, is 0.25 mR/hr.

MR. VILLFORTH: Let me go back again. In the case of color television receivers, the exposure rate is measured at 5 centimeters. In ANSI 43.1, I think it is also to be measured at 5 centimeters. You don't spend too much time 5 centimeters from an x-ray diffraction unit, do you? You don't spend too much time 5 centimeters from the surface of a color TV set? So these numbers should not be confused with exposure limits for people. The number for color TV was derived from consideration of NCRP recommendations. They felt that for television receivers the x radiation should be about 5 percent of natural background to the viewer.

When you start from that point, and you consider the viewing time, the viewing distance, the air attenuation of the x radiation, etc., you arrive at the number that happens to be 0.5 mR/hr at 5 cm from the surface. That number should not be confused with a personnel exposure limit or radiation protection guide.

DR. RUDMAN: I would like to ask a question concerning the possible adoption of some of these guides and standards by State agencies which can be stricter than the Federal regulations.

For example, in the forthcoming ANSI report, there is a distinction made between the different types of instrumentation. What is there to prevent a State government from perhaps employing people who are not aware of the inherent difficulties or differences in the instruments, from choosing the strictest regulations, and applying those to all x-ray instruments that come into their State? That will drastically restrict the use of the equipment by people who are qualified to use it.

MR. VILLFORTH: Again, we are talking about performance standards for the manufacture of equipment. I do not think it is permissible under the Act for a State to establish equipment performance standards that are different from the Federal performance standards. States may set standards of use, however.

MR. ASHBY: I mentioned that there are conditions existing where there are different regulations in different States imposed upon the equipment. There are 22 agreement States. Each of them has a section on medical diagnostic x rays. NCRP-33, for example, designates 10R per minute skin dose at 18 inches from the focal spot. All agreement States, except one, have adopted that 10R per minute. This State has specified 6R per minute. So, for example, our equipment installed in that State has to be modified to provide no more than 6R per minute. In the rest of the States, 10R is what is specified. So, some of the conditions already exist.

DR. RUDMAN: I am hoping, perhaps, that the Federal agency responsible can perhaps send guidelines out to the State agencies, indicating that there are inherent difficulties and that the States should check into them before they pass any regulation.

MR. LUBENAU: John could answer it just as well and probably better than I. There are mechanisms to insure at least some degree of compatibility between individual States' programs and also between Federal programs; for example, between the AEC and the agreement States. The PHS and the AEC are very instrumental in drawing up a standard document for State regulations. This is the document which most of the States use in writing regulations. You will find individual cases where there are differences.

But, by and large, I think that there are effective mechanisms to assure a good degree of compatibility from State to State.

Your problem, I think, will not be so much differences in the regulations as differences in the administration of the regulations.

MR. VILLFORTH: I would like to point out the results of a recent survey of the States. It was found that 42 of the States have enforceable regulations for industrial x-ray radiographers and for other nonmedical x-ray equipment, including x-ray diffraction. Of the 42 States which have enforceable regulations in the above-mentioned areas, 36 possess regulations which are in substantial agreement with the Council of State Governments' suggested regulations for industrial x radiographers. The Council of State Governments is that organization which provides continuity for various State regulations.

MR. O'BRIEN (Brookhaven): I have two short comments. First of all, very little has been said explicitly about eye exposure in these 2 days. I personally feel that that is probably the most serious hazard potential from x-ray diffraction equipment, and I would like to suggest that whoever is preparing the proceedings might include some reference material, literature that might be pertinent to that.

My second comment is that a lot of the safety equipment, such as shutters, interlocks, and devices that have been spoken about here, is not familiar to me as to sources. I admit that I am not that involved in x-ray diffraction work. But I feel that probably some of this is commercially available and other is homemade. And I would like to suggest that perhaps someone collect some of these various types of equipment and publish a manual or perhaps an appendix to the proceedings, something like a hot lab equipment manual that some of us have seen.

DR. BLOCK: Number one, about the eyes. In the draft of the ANSI, we specifically recommend that people should consider wearing lead glasses when they are working.

As for the shutters that you are speaking about, there is a report that was prepared several years ago by the American Crystallographic Association, Apparatus and Standards Committee, chaired by Karl Beu.

After this meeting, I am going to ask Professor Samson of the ACA Committee whether he can work on preparing a revised version and also incorporating some of his own ideas. As soon as Professor Samson does that, the new version will also be distributed as an ACA report.

DR. SAMSON: I have a question regarding the terminology. I would like to make sure that the terminology used, when we talk about leakage, is really clearly understood, before even the attempt of any legislation is made.

When we use the term "leakage", it should be clearly understood that we are talking about the direct flow of x rays from the source to the outside and not any secondary scatter from the sample, half-scattering, and so on. One is avoidable, and the other one can be reduced to within a reasonable limit.

I would like to be sure that those terms are firmly understood and that they will be clearly distinguished in any effort of the legislation.

MR. VILLFORTH: Professor Samson, let me say that I think I understand them. The analogy is very similar to the medical-dental x-ray area where we have a specific definition for diagnostic tube housing leakage. There is a similar analogy to the scatter radiation that we are concerned with in medical x radiation. There would have to be a group of definitions in any regulation that would be promulgated, and your point would have to be considered.

DR. BLOCK: Behind practically all of the remarks from the members of the ACA is a great worry that we will not be able to carry out experiments. Certainly we are all in accord with the requirements of safety, but be very careful not to make regulations so restrictive for everyone that scientists will not be able to carry out their experiments.

MR. GORSON: Of course, it is not entirely up to the Bureau. There is an expert committee of 15 people who will share the responsibility for reviewing these standards. Knowing some of the people personally, I don't think it is very likely that anything that drastic could happen.

VOICE: The health physicists are really going to be the ones who are going to enforce user standards. So, what we are talking about emphasizes that all of you health physicists must work with the diffractionist and not be a burden on his experiment. Work along with us and we will work along with you.

MR. ASHBY: I would like to get one more plug in for the manufacturer on the subject of leakage. We, the manufacturers, are taking the brunt of the regulations of the Bureau of Radiological Health. But you must recognize that it can only go so far. For example, when we install equipment in your laboratories we lose control over it.

I looked at some of the equipment that was in the slides this morning. One machine was mentioned to be an old G.E. generator of about 23 years of age. If my memory serves me right, that was originally made as a half-wave rectified unit. It is updatable to a full-wave rectified. In fact, it can have a large capacitor put on it and it becomes a constant potential generator. At this point, you have about tripled the radiation output of that original design. We cannot predict the future modification of some of our equipment, so, after the equipment is delivered to you, it is in your hands, not ours. We can't control that kind of modification. And, at that point, yes, you need to wrap lead foil around it or have us rebuild the unit.

MR. INGLES: Is the Bureau going to adopt the ANSI standard for implementation?

MR. VILLFORTH: Not necessarily, but we have to take it into consideration in developing a performance standard for equipment.

MR. INGLES: Once the ANSI standard is a firm fact, you won't be implementing it?

MR. VILLFORTH: No. Because some of the aspects of ANSI are not directed to performance standards of equipment. They are also involved in the installation and use.

MR. INGLES: But the parts which are performance standards, you will then abstract from ANSI or you will refer to them? You will be using the ANSI, won't you?

DR. BLOCK: Could I answer that? I don't think they should, because the Bureau has a legal responsibility to carry out. ANSI is a completely different approach. It is a voluntary organization in which there are representatives from the entire world of technology.

My involvement in ANSI has enlightened me in all the requirements from different organizations' points of view, all the way from the manufacturers, the labor unions, the Public Health Service, insurance companies, and so on. But there is a problem; you try to get unanimous agreement, although it is not required. So, you have, essentially, the lowest common denominator. I consider our mission as a subcommittee is to educate, if I may use the word in the broad sense. I was told, when I was given responsibility for N43.1, not to expect any standards out for 5 years. The Bureau, with its greater authority, can promulgate standards which might be stricter than ANSI. I certainly hope they are no less strict than ours.

MR. ROGER GRANLUND (Penn State): I want to make a comment about scatter radiation. I want to apologize to Dr. Samson that some health physicists use leakage and scatter interchangeably. I think we know the difference between the two.

My comment, however, concerns any performance standards that regard scatter radiation. Indeed, scatter radiation is inevitable if you have open systems. But it should not be disregarded. It should not be taken as something that we have to live with. Anyone who has used diffraction equipment knows that there is a world of difference between the various manufacturers as to the amount of scattered radiation. And some of the most commonly used units have very little or almost no protection against this scattered radiation.

So, it is all well and good to shield against leakage from the primary beam, but I think that most of the general radiation comes from scatter. This should not be completely ignored. There should be some sort of standard.

DR. BLOCK: This is what I tried to say. There should be really two types of equipment; one for the repetitive use, which could be absolutely safe for ordinary purposes, and the other one for research purposes, where you are relying very much on the training and experience of the worker.

MR. SHAW: I think we have to worry more about how to use the equipment and in what circumstances to use it.

What I would like to see is positive recommendations for using equipment. Should I wear a film badge? Should I have a blood test once a week? Should I put one piece of equipment in the room or two pieces or three pieces? If I make my own modifications, what sort of radiation level, checking with a monitor, is safe for me to use? I think this sort of thing is very much more important than whether I can get 1 or 2 mR/hr from some newly installed equipment.

DR. BLOCK: Let's make it clear that when we have said tinfoil we meant lead foil.

CLOSING REMARKS

John W. Thomas
and
Rodney Ice, Ph.D.

CLOSING REMARKS

John W. Thomas

Before we adjourn, an observation may be appropriate on what may be said today of the success of this conference. It was planned with the belief that Radiation Safety in X-ray Diffraction and Spectroscopy was an important subject that would benefit from mutual discussion by the various areas of interest concerned. I think this has been done well; that we have had a mutually advantageous exchange of information and special knowledge.

The discussions of the past 2 days have delineated a number of areas where we should seek improvements in equipment, assessing the best in protection surveys and survey equipment, assuring that operators are well and properly informed of hazards and protection measures, and a number of others. In informal discussions much has been said pro and con regarding the use of "tin foil." This not uncommon practice of using thin lead sheets as flexible, supplementary shielding to compensate for poor coupling and a variety of other sources of unecessary stray radiation is probably a good indicator of the current status of radiation protection in x-ray diffraction and fluorescence. I suggest that if it be used with knowledge, tin foil has considerable value at this time as an interim means of dealing with exposure problems. However, all deliberate haste is in order to render its value increasingly obsolete.

This conference has not produced even minimal performance criteria or standards, and some may be disappointed that it has not. It was not our plan or intention to do so. The conference and its published proceedings were planned to provide an evaluation of the problem,a discussion of the status of radiation safety in x-ray diffraction and spectroscopy, some identification of special problem areas, and some indication of what is to be done. I think that we have succeeded in bringing together information that can be of great help to regulators, standards-making bodies, manufacturers, health physicists, educators, and equipment users in improving safety-related practices and equipment features in x-ray diffraction and spectroscopy. If I am right, the conference has been well worthwhile.

As we now close, special thanks are due to many groups and persons associated with the Conference:

To the Bureau of Radiological Health, U. S. Public Health Service, for financial support for partial expenses and the published Proceedings.

To the Sponsors.

To the Conference Committee.

To the Laboratory for Research in the Structure of Matter (LRSM) of the University of Pennsylvania for the fine facilities, and to Henry Katz of the LRSM who arranged the X-ray Laboratory visits on Tuesday evening.

To the office staff of the Radiation Safety Office of the University of Pennsylvania, Carla Hudson, Cindy Amicone, Bill Hoffman and Joe Kane, who have taken care of all the details of registration, refreshments and visual aids.

To the excellent speakers and session moderators.

To each and every attendee.

CLOSING REMARKS

Rodney Ice, Ph.D.

I would like to say one other word of thank you here. It takes a lot of work to put on a program of this magnitude, and there always has to be one person who gets in and pushes the ball and keeps everybody rolling along.

This one person in this case is Mr. John Thomas. He has been working on this conference for a period of one year. When you realize that this is in addition to his regular job, you will realize that this is a labor of love. I think we owe a great deal to John Thomas for bringing together the user and the health physicist. Although they may not have liked it, the marriage is here, it is upon us, and I think it is the first step in the right direction.

APPENDIX A

LIST OF REGISTRANTS AT CONFERENCE ON RADIATION SAFETY IN X-RAY DIFFRACTION AND SPECTROSCOPY

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